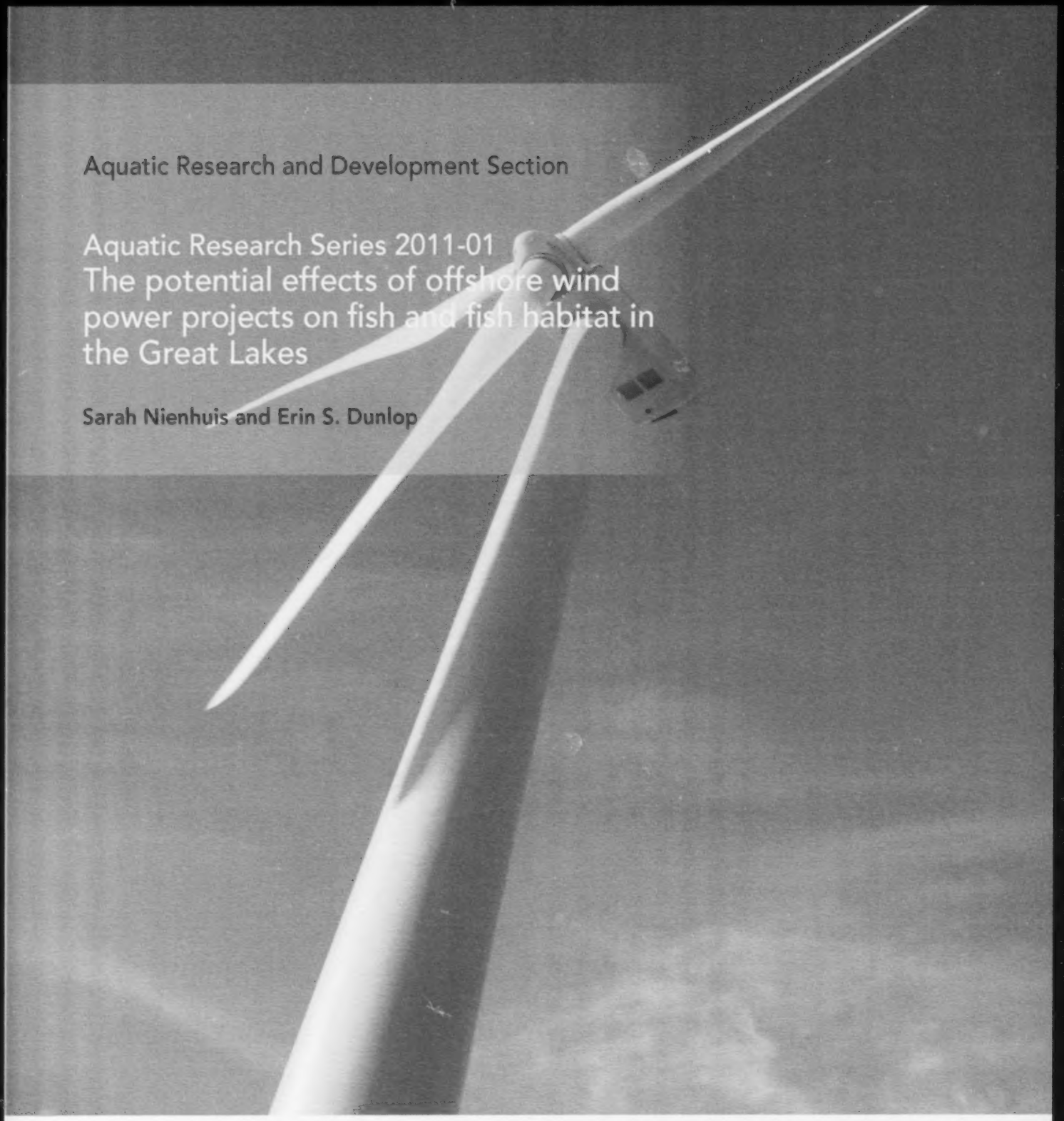

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The potential effects of offshore wind power projects on fish and fish habitat in the Great Lakes

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Abstract

In an effort to reduce greenhouse gas emissions and mitigate impacts of climate change, many nations are promoting the development of renewable energy technologies— including wind power generation—to replace fossil-fuel based energy production. Owing to their strong and constant wind speeds, the Great Lakes are a candidate for future development of offshore wind facilities. Drawing from the marine literature as well as upon knowledge of Great Lakes ecosystems, we conducted an assessment of the potential effects of offshore wind power projects on Great Lakes fish and fish habitat. Upon review, potential effects of relevance to Great Lakes fish include injury or behavioural disturbance from the high-intensity noise generated during construction; masking of fish communication from the noise produced during turbine operation; disorientation or disruption of migration from electromagnetic fields emitted by submarine cables; enhanced foraging opportunities or spawning habitat at turbine foundations; and the protection of fish from harvest by the possible creation of fishing exclusion zones within the wind power project area. Furthermore, despite many parallels, two effects that may be of greater concern in the Great Lakes than in marine environments are the creation of habitat suitable for colonization by invasive species upon submerged turbine structures, and the potential remobilization of sediment-bound contaminants from dredging activities. Owing to the lack of experience with offshore wind facilities in freshwater environments, the magnitude and significance of many of these potential effects to Great Lakes fish remain uncertain. However, although the effects of offshore wind power projects might not be inconsequential, their ecological footprint within the Great Lakes could be relatively small if site selection is precautionary, mitigation measures to reduce negative impacts are adopted, appropriate biological monitoring is conducted, and options to enhance possible benefits are implemented.

Résumé

Dans un effort pour réduire les émissions de gaz à effet de serre et atténuer les effets du changement climatique, de nombreuses nations favorisent le développement des technologies d'énergie renouvelable — notamment la production d'énergie éolienne — en remplacement de l'énergie dérivée des combustibles fossiles. À cause de leurs vents forts et constants, les Grands Lacs constituent l'endroit par excellence pour l'installation d'éoliennes marines. À partir de la documentation marine et de la connaissance des écosystèmes des Grands Lacs, nous avons effectué une évaluation des effets potentiels des projets d'énergie éolienne marine sur le poisson des Grands Lacs et sur son habitat. Notre examen a révélé des effets potentiels propres aux Grands Lacs, soit des blessures ou des perturbations comportementales résultant du bruit à haute intensité provoqué par la construction; le masquage des communications entre les poissons résultant du bruit du fonctionnement des turbines; la désorientation ou les perturbations du mouvement migratoire provoquées par les champs électromagnétiques émis par les câbles sous-marins; l'augmentation des aires d'alimentation et de fraie au pied des turbines; la protection contre la pêche à cause de la création possible de zones d'exclusion de pêche dans les secteurs des éoliennes. De plus, en dépit de nombreux parallèles, deux effets pourraient être beaucoup plus préoccupants dans les Grands Lacs que dans les autres milieux marins, soit l'apparition d'un habitat favorisant la prolifération d'espèces envahissantes en présence des structures de turbine submergées, et la remobilisation possible de contaminants liés aux particules découlant des activités de dragage. En raison de la faible fréquence des éoliennes marines en eaux douces, l'ampleur et l'importance des nombreux effets possibles sur les poissons des Grands Lacs demeurent incertaines. Toutefois, même si les effets des projets d'éoliennes marines puissent ne pas être sans conséquence, leur empreinte écologique dans les Grands Lacs pourrait se révéler relativement faible, si le choix de leur emplacement est prudent, si des mesures d'atténuation des effets négatifs sont adoptées, si une surveillance biologique est assurée et si des options visant à augmenter les avantages possibles sont mises en place.

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Executive Summary

While there currently exists little opportunity to assess the effects of offshore wind developments in freshwater ecosystems directly, a review of the available scientific and grey literature related to offshore wind projects in the marine environment, coupled with current knowledge of Great Lakes ecosystems, can provide insight into effects that could arise within the Great Lakes. In this report, we review what we expect to be the major categories of effects associated with the construction and operation of offshore wind facilities in the Great Lakes as they relate to fish and fish habitat. Key findings of this report include:

- Although termed "offshore wind power projects", associated turbine arrays and cables could often be located within the nearshore zone of the Great Lakes.
- Noise generated during construction could be substantial and is of sufficient intensity to potentially cause significant physiological damage to fish and is therefore among the most serious effects to be considered.
- Remobilization of sediment-bound contaminants is possible during construction, and could result in the bioaccumulation of heavy metals and organic pollutants in fish.
- Among the most significant knowledge gaps is our ability to forecast the effect that electromagnetic fields created by submarine cables and noise generated during turbine operation will have on fish distribution and migration.
- Creation of artificial reefs at turbine foundations could enhance foraging opportunities and provide spawning habitat for fish, but at the same time could promote the range and population expansion of certain invasive species.
- Commercial fishing exclusion zones around turbines and cables could act as sanctuaries and increase fish biomass in those areas.

Although there are many parallels, offshore wind power projects in the Great Lakes are likely to differ from those in marine systems and from other development activities in several key ways. Two differences between offshore wind power projects in the Great Lakes and the marine environment are the creation of habitat suitable for invasive species at the base of wind turbines and the redistribution of contaminated sediments from dredging activities. Being less of an issue in marine systems, these effects haven't received much attention in the marine literature and will need further research efforts to fully understand. Offshore development projects are already commonplace in the Great Lakes and include the construction of bridges and piers, for example. Some of the effects described in this report may overlap with the effects of these activities. However, there are many unique attributes of offshore wind power projects that will make their effects different from other anthropogenic activities. Most notably, pile driving activity is expected to occur for longer periods and over a larger spatial scale than is needed for other forms of offshore development; noise generated from turbine operation will be above detectable background noise levels for the duration of the operational phase of wind power projects; turbines will likely be placed further offshore than most other forms of development; and extensive submarine power cabling connects turbines and runs ashore. Although the effects of offshore wind power projects might not be inconsequential (Table 1), their ecological footprint within the Great Lakes will depend on many factors but could be relatively small if certain precautions and mitigation actions are adopted and care is taken as to their placement.

Table 1. Predicted magnitude of various effects of offshore wind power projects on fish and fish habitat in the Great Lakes. Magnitude levels are High, Medium, and Low. Degree of uncertainty and magnitude of effects are relative to other effects from offshore wind power projects listed in this table. Magnitude, timeframe, and spatial extent of effects are based on current knowledge and are predictions for a typical wind power project. All effects will be a function of the location and size of the wind power project. Benefits could be enhanced or negative impacts could be reduced with appropriate mitigation. Effects with High uncertainty are highlighted and are of high priority for future research. Not all possible effects are listed in this table (see report text for details).

Effect	Associated wind power activity	Direction of effect (negative impact or of benefit to fish or fish habitat)	Predicted magnitude of effect	Degree of uncertainty in predicting magnitude of effect	Main factors that will influence the magnitude of effect	Timeframe of effect	Spatial extent of effect
Disturbance or injury to fish from underwater noise during construction	Construction (mainly pile driving)	Negative	High	Low	Species-specific sensitivity to noise	Several months to over a year	Wind power project area and beyond
Release of contaminants	Construction (dredging, cable trenching)	Negative	High	Low	Degree of contamination in sediments; species-specific sensitivity and ability to bio-accumulate; local conditions (e.g. currents)	Several months to over a year	Wind power project area and cable route; possibly beyond
Disturbance to fish from underwater noise during operation	Turbine operation	Negative	Medium	High	Species-specific sensitivity to noise; wind speeds; foundation type; amount of habituation to noise	20-25 years	Wind power project area and beyond
Disruption of fish distribution or migration from electromagnetic fields	Operation of submarine power cables	Negative	Medium	High	Species-specific sensitivity to electromagnetic fields; cable properties; location of cables relative to migration routes	20-25 years	Mainly within wind power project area and cable route; possibly beyond for some species
Sedimentation and turbidity from construction activities	Construction (dredging and cable trenching)	Negative	Medium	Low	Presence of sensitive life stages and species; local substrate type and habitat features; local conditions (e.g. currents, wave strength and direction)	Several months to over a year	Immediate vicinity of turbine foundations and cables; possibly beyond

Effect	Associated wind power activity	Direction of effect (negative impact or of benefit to fish or fish habitat)	Predicted magnitude of effect	Degree of uncertainty in predicting magnitude of effect	Main factors that will influence the magnitude of effect	Timeframe of effect	Spatial extent of effect
Creation of hard substrates suitable for colonization by non-native species could promote range or population expansion of non-native species	Physical presence of structures	Negative	Low	High	Scour protection materials; project location	20-25 years; longer depending on decommissioning activities	Turbine foundations (<1% of wind power project area); possibly beyond if turbines act as stepping stones
Loss of access to recreational and commercial fishing	Construction and operation	Negative	Low	Medium	Will be highly dependent on project location relative to fishing grounds; access rights	20-25 years	Around turbine foundations and cable routes; possibly entire wind power project area depending on access rights
Alteration of currents, wave strength, and wave direction	Physical presence of structures	Negative	Low	Medium	Location of wind power project and local features; species and life-stage specific sensitivity to currents; scour protection	20-25 years; possibly longer depending on decommissioning activities	Most severe effects will be in immediate vicinity of turbine foundations; effects beyond wind power project area possible
Altered sediment transport and deposition from physical presence of turbines and foundations	Physical presence of structures	Negative	Low	Medium	Local physical features; water currents; presence of sensitive life stages and species; scour protection	20-25 years; possibly longer depending on decommissioning activities	Most severe effects will be in immediate vicinity of turbine foundations; effects beyond wind power project area possible
Habitat loss	Dredging activities; physical area occupied by turbine foundations and cables	Negative	Low	Low	Location of wind power project; whether cables are buried or not; presence and size of scour protection; foundation type	20-25 years; possibly longer depending on decommissioning activities	Turbine foundations and cables (<1% of wind power project area)

Effect	Associated wind power activity	Direction of effect (negative impact or of benefit to fish or fish habitat)	Predicted magnitude of effect	Degree of uncertainty in predicting magnitude of effect	Main factors that will influence the magnitude of effect	Timeframe of effect	Spatial extent of effect
Habitat creation (enhanced foraging, refuge from predators, spawning habitat)	Physical presence of structures	Benefit	Medium	High	Materials used for scour protection; project location; size of scour protection; species-specific habitat and spawning preferences; extent to which species are affected by noise, electromagnetic fields and other disturbance from wind power project	20-25 years; longer depending on decommissioning activities	Turbine foundations and scour protection
Protection of fish from commercial fishing in and around turbines and cables could increase fish biomass as in a sanctuary or marine protected area	Operation	Benefit	Low	High	Access rights to area; project location relative to fishing grounds; extent to which fish are affected by noise, electromagnetic fields and other disturbance from wind power project	20-25 years	Around turbine foundations and cable routes
Enhanced recreational fishing opportunities (through the artificial reef/fish aggregating effect)	Physical presence of structures	Benefit	Low	High	Access rights to area; project location; size and nature of scour protection; extent to which fish are affected by noise, electromagnetic fields and other disturbance from wind power project	20-25 years; longer depending on decommissioning activities	Around turbine foundations and scour protection

1. Introduction

In order to reduce and potentially mitigate further deleterious impacts of global climate change, most industrialized nations have set targets to minimize greenhouse gas emissions. As part of this commitment, renewable energy technologies are now being developed and implemented with the hope that these will reduce our reliance on fossil fuel-based energy production. Wind power is among the existing options for renewable energy generation and has seen a rapid expansion in recent years. While the use of wind turbines to harness wind energy is by no means a new concept, offshore wind energy production is still an industry in its infancy. However, because of the benefits of stronger and steadier wind speeds offshore and the potential for less visual and noise disturbance to humans, offshore wind production is set to expand dramatically in the years to come. Not only are coastal nations expected to continue the expansion of offshore wind power projects in the marine environment, but nations with freshwater coastlines are also projected to utilize these offshore environments for wind energy production as well. Specifically, the U.S. and Canadian governments have recently agreed to consider the future construction of offshore wind power projects in the Great Lakes.

1.1 Project background and scope

The Aquatic Research and Development Section of the Ontario Ministry of Natural Resources is providing two science-based reports to the Renewable Energy Program relating to offshore wind power projects[1] and effects on fish. The reports will review (a) the potential effects, including any adverse impacts or benefits, of offshore wind power projects on Great Lakes fish and fish habitat, (b) options to prevent or mitigate adverse impacts and promote or enhance the beneficial aspects of forthcoming projects and (c) guidelines for monitoring impacts and options to aid in the development of best management practices. While options to mitigate some of the adverse impacts and enhance potential benefits of offshore wind facilities are briefly reviewed here, along with a few key options for monitoring and for development of best management practices, more detailed discussion of these topics will be provided in the second, accompanying report. This first report focuses only on the potential effects of offshore wind power projects on fish and fish habitat (which includes impacts to invertebrate species where relevant) and does not address

[1]Terminology note: We use the Ontario Ministry Natural Resources standard "wind power project" in place of "wind farm".

effects on terrestrial habitats or organisms such as birds or bats. We begin by first outlining some of the technical aspects of offshore wind power projects, such as activities involved in construction and materials used, to provide some context for a discussion of potential effects.

1.2 Types of structures used in offshore wind power projects

Though the marine and freshwater environments are fundamentally different, the technology used for offshore wind energy production in the Great Lakes will be similar to existing wind power projects in marine waters. This generally involves the use of horizontal axis, traditional fixed-bottom wind turbine technology (Fig. 1). Individual turbines are comprised of three basic components: a rotor with three blades mounted on a hub; a nacelle which houses the gear box and electrical generator; and the tower or main shaft which is supported by the foundation. Common 2.5 MW and 3 MW offshore turbines have tower heights of 75-100 m and 100-120 m, respectively. Rotor blades are typically made of a fibreglass laminate or epoxy-based composite materials, and currently have maximum diameters of approximately 100 m. These sizes are reflective of existing prototypes, though the trend is toward ever-larger blade and turbine sizes with higher energy output. The number of individual wind turbines within an offshore wind power project typically ranges from 50-100. In order to minimize wake losses due to neighbouring turbines, spacing between turbines within a wind power project is typically 5-10 rotor diameters, or approximately 500 - 1000 m apart for the larger turbines.

There are three common foundation types for offshore wind turbines; monopile, gravity and tripod foundations (Fig. 1). Monopile foundations are the most common and consist of a single large, hollow steel pipe 4-6 m in diameter that is driven or drilled approximately 25-30 m into the sediment. They are most often used in stiff or sandy substrate types where water depths are less than 25 m. Gravity foundations are used in shallow (usually <15 m) areas where drilling or pile driving is not feasible. They consist of a large base made of steel or concrete which rests atop a levelled area of the lakebed, meaning that their installation often requires extensive dredging and site preparation. These foundations rely upon the weight or gravity of the structure to resist overturning. Although much less common, tripod foundations similar to those employed

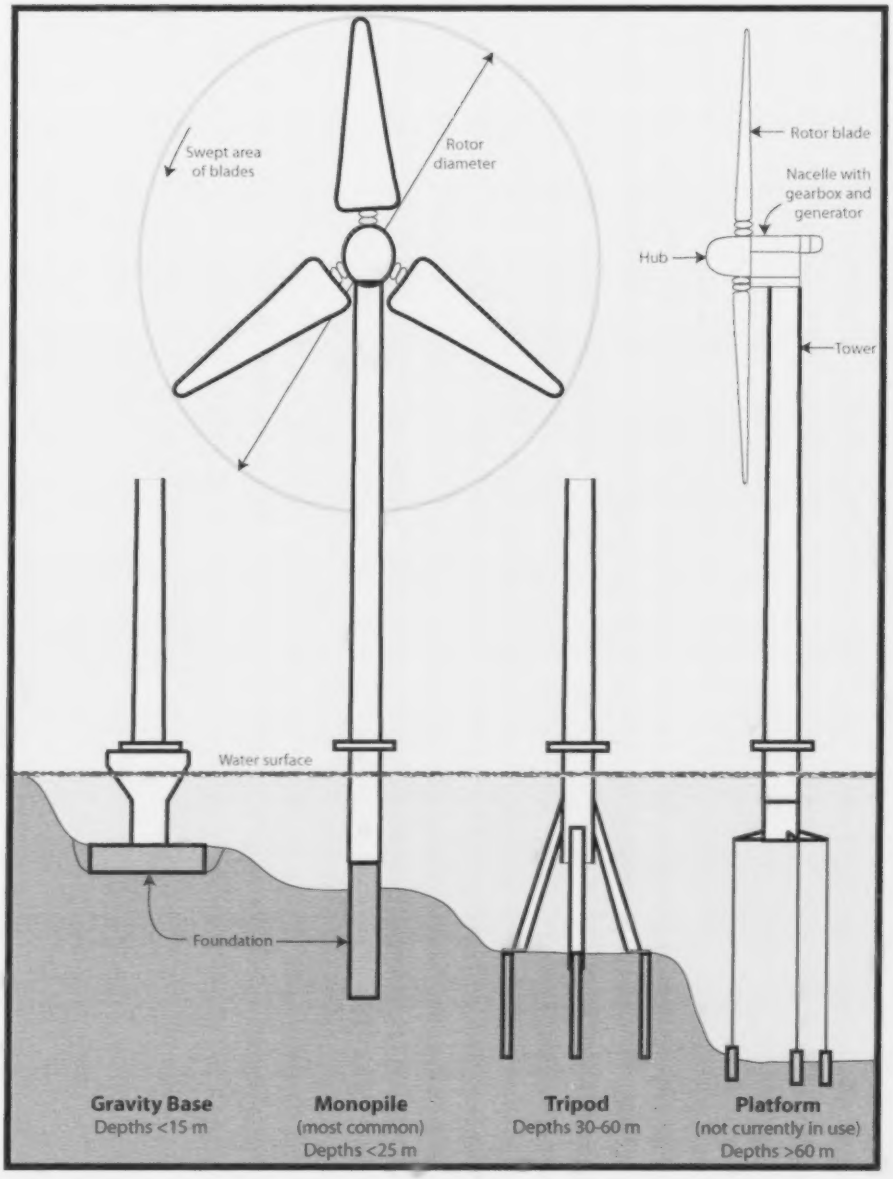


Figure 1. Example offshore wind turbine foundation types in use or proposed (bottom of figure) and key components of a typical wind turbine (top of figure). The typical depths for the different foundation types are given. The monopile foundation is the most commonly used for offshore turbines and will most likely be used in the Great Lakes, with the addition of conical ice collars as depicted for the gravity base foundation. Note that other floating turbine concepts have been proposed. This figure is for illustrative purposes only and is not to scale.

by the offshore oil and gas industry have been used as turbine foundations in deeper waters (30-60 m). Tripod foundations are anchored by multiple smaller piles (0.8-2.5 m in diameter) that are driven or drilled 10 m or more into the sediment. While they have not yet been employed on an industrial scale in the offshore environment, floating turbines that would be anchored to the bottom and buoyed up at the surface (Fig. 1) are in the development stages for deeper water areas (i.e. 60-900 m). However, it is not likely that floating turbines will be used in the Great Lakes any time in the near future, if at all.

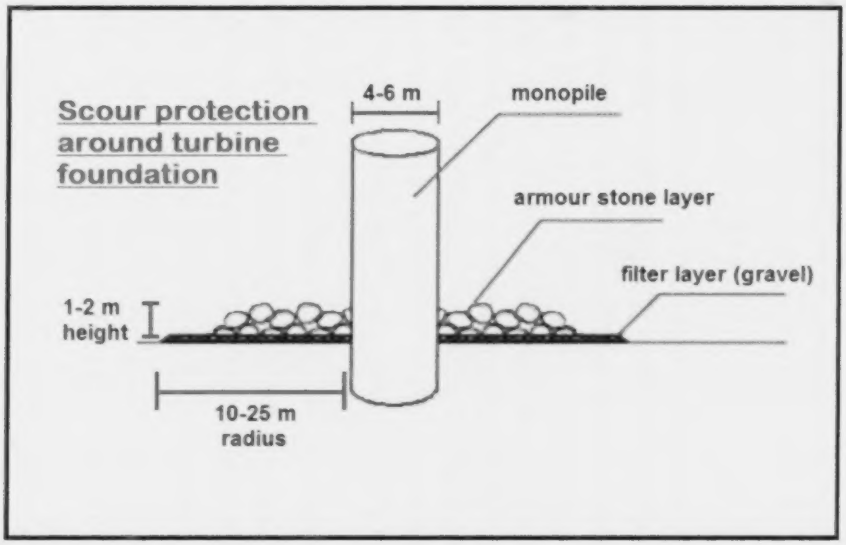


Figure 2. Illustration of scour protection at the base of a monopile wind turbine foundation.

In order to resist scouring or erosion, scour-protecting revetments consisting of large rock and boulder "rip-rap" are typically piled around the base of wind turbine foundations (Fig. 2). Several layers of rock with increasing rock diameter are often piled around turbine bases, with a standard radius extending approximately 10 m (Wilson & Elliott 2009) up to 25 m (Baker 2003) out from the foundation base of the monopile. To prevent corrosion of the steel foundations in marine environments, glassflake reinforced polyester coating or cathodic protection is often employed (Wilhelmsson & Malm 2008), though this may not be necessary in freshwater environments. Other types of materials, for example, synthetic bags filled with sand, could also be used as scour protection. Finally, because the Great Lakes are prone to extensive ice cover in

winter months, conical collars or ice cones will probably be installed on the towers at water level in order to prevent structural stress or scour from ice build-up.

1.3 Life-cycle of an offshore wind power project

The lifecycle of an offshore wind power project involves several distinct phases, each with their own potential effects on aquatic organisms and habitats. The pre-construction or site-exploration phase is the first, and can range from 1-5 years. Prior to the installation of wind turbines, appropriate sites for their placement must first be selected and inspected to ensure optimal operating conditions. Meteorological masts are commonly installed at potential sites a year or more before construction begins in order to measure wind speeds and yields and other information such as wave height. In addition, geophysical and geotechnical surveys are conducted to determine lake bed morphology and substrate types. This information is used to assess the suitability of a location for the turbine foundations, as well as to guide foundation design.

After a suitable site has been selected and studied, the construction phase begins. Depending on the number of turbines being built and on weather conditions, the construction phase can last a year or more. During this phase, the turbine foundations are installed first. For monopile foundations this would involve pile driving and, if hard chalk or bedrock is present, may also require drilling. In the case of gravity foundations, installation usually requires sediment dredging to level the surface of the lake bed before the base can be laid. Once the foundations are installed, large barges transport the pre-fabricated turbine structures to the site, and jack-up barges with cranes are used to put them in place. Submarine cables connecting the turbines to each other, to substations and then to shore are also installed. These cables are either embedded several meters under the lake bed—accomplished using remotely operated vehicles or water jetting to dredge out a trench in sandy or clay bottoms—or laid atop the sediment and buried with concrete mattresses or rock in areas with rocky bottoms. The long cables connect with onshore power facilities, where horizontal directional boring is often employed to avoid potential damage or disturbance to the cables from waves in the nearshore area.

Once installed, offshore wind turbines are expected to operate for a period of 20-25 years. During the operational phase, periodic inspection and maintenance will be required, which would

involve routine tune-ups, minor repairs, and other upkeep procedures to keep the turbines running efficiently. After the operational life-time of the turbines has expired, the final phase is decommissioning. Whether all or only parts of the turbine structures will be removed during this phase remains to be seen. However, if entire foundations need to be removed, this may require the use of explosives and underwater detonations, procedure which is common for the decommissioning of offshore oil and gas installations.

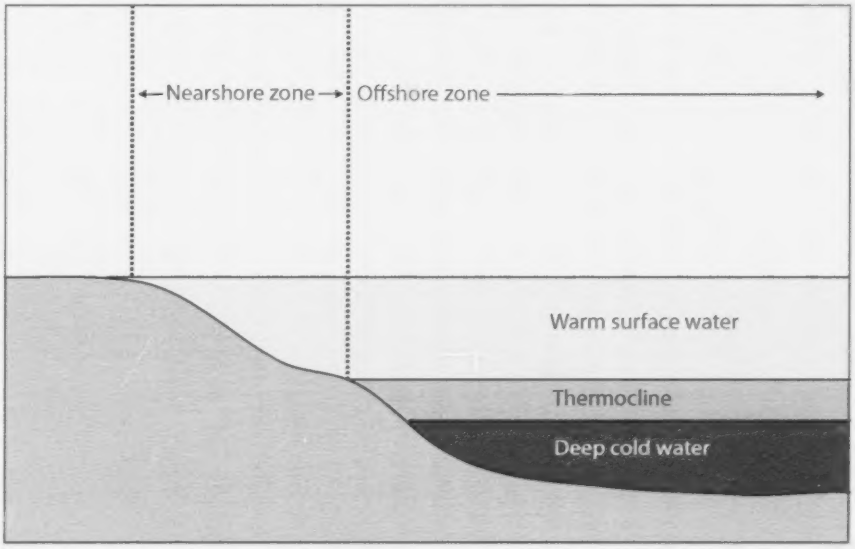
1.4 Potential locations of offshore wind power projects in the Great Lakes

The current state of offshore wind power technology involving fixed-bottom wind turbines constrains the location of offshore wind power projects to water depths between 5-30 m. Tentative nearshore exclusion zones of 5 km and 6 miles have been proposed for wind power projects in Ontario and Michigan, respectively. However, the technical and physical requirements for suitable site selection could negate the feasibility of these minimum distances in some cases. In order to facilitate the delivery of wind energy generated by offshore turbines and reduce transmission lengths, it is likely that wind power projects in the Great Lakes will initially be located in areas close to existing power grid infrastructure. Because of their location within the highly populated eastern seaboard, with a large potential market and grid connectivity nearby, areas along Lake Erie and Ontario would therefore be good potential candidates for offshore wind turbine installations. In addition, because it is shallow enough to allow for fixed-bottom structures over most of its extent, Lake Erie may be expected to house the highest concentration of wind power projects of all the Great Lakes.

Within Ontario, an offshore wind power project is any wind power project that is placed within the aquatic environment as opposed to on land. It is important to note however, that an offshore wind power project could be placed within what is defined by ecologists as the *nearshore zone* (Box 1). In fact, given the limitations of current technology which necessitate placing offshore wind power projects at depths of less than 30 m, the majority of projects are likely to be situated in the nearshore zones of the Great Lakes. This has implications for the species assemblages that could be affected by offshore wind power projects.

Box 1: Nearshore and offshore zones of the Great Lakes

Limnologists and aquatic ecologists distinguish between the nearshore and offshore zones of a lake, recognizing that there are specific biological, physical and ecological processes that occur within these zones. For the purposes of this report, we adopt the Environment Canada definition and refer to the nearshore zone as that beginning at the shoreline (or lakeward edge of a coastal wetland) and extending to where the thermocline intersects the lake-bed in the summer/fall (Edsall & Charlton 1997). The nearshore zone therefore represents a band of varying width around each lake that falls between the shoreline and the deeper offshore zone. The boundary of the nearshore and offshore zone can occur at a depth of about 10 m in Lake Superior (the deepest and coldest lake), but as deep as 30 m in the other Great Lakes. The habitat complexity and number of fish species tends to be greater but the degree of environmental degradation tends to be higher in the nearshore relative to the offshore zone.



Source: Edsall and Charleton (1997)

1.5 Effects on Great Lakes fish and fish habitat

The proposed installation of wind power projects within the Great Lakes raises concern for the aquatic inhabitants of these important freshwater ecosystems. Specifically, economically and ecologically valuable species of Great Lakes fish could be affected by the construction or operation of wind turbines. At the time of completion of this report, there only exists a single, small-scale offshore wind power operation in freshwater; all remaining projects to date have been in marine systems. In order to assess how Great Lakes fish might respond to these novel features within the aquatic landscape we have conducted an extensive review of the current scientific and grey literature, where various effects have been reported for marine species in response to the development of wind power projects in coastal marine environments. In addition, we draw from experimental studies that have measured the physiological or behavioural responses of various fish species to different stimuli or disturbances known to be associated with wind power project construction or operation. Finally, we attempt to link the gap between observed effects of wind power projects on fish in marine systems and those that might be expected in freshwater systems based on knowledge of the biology and life history of Great Lakes fish species. The following is a review of the potential effects, including possible adverse impacts and benefits, of offshore wind power projects on Great Lakes fish and fish habitat, broken down into several different effects categories and highlighting effects on specific Great Lakes fish species where possible. Fig. 3 provides a summary of the expected effects.

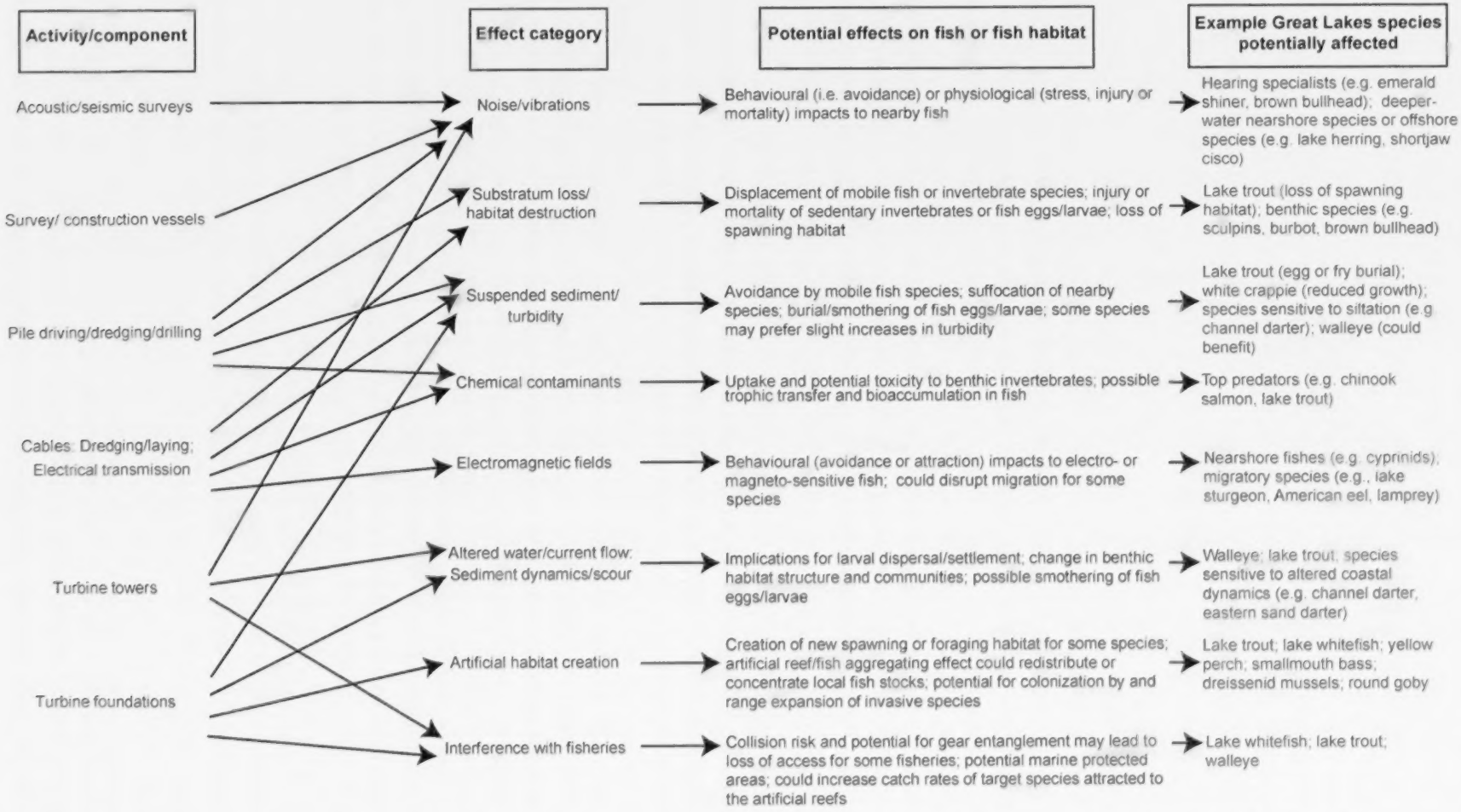

Activity/component
Effect category
Potential effects on fish or fish habitat
Example Great Lakes species potentially affected
Acoustic/seismic surveys
Survey/ construction vessels
Pile driving/dredging/drilling
Cables: Dredging/laying; Electrical transmission
Turbine towers
Turbine foundations
Noise/vibrations
Substratum loss/ habitat destruction
Suspended sediment/ turbidity
Chemical contaminants
Electromagnetic fields
Altered water/current flow; Sediment dynamics/scour
Artificial habitat creation
Interference with fisheries
Behavioural (i.e. avoidance) or physiological (stress, injury or mortality) impacts to nearby fish
Displacement of mobile fish or invertebrate species; injury or mortality of sedentary invertebrates or fish eggs/larvae; loss of spawning habitat
Avoidance by mobile fish species; suffocation of nearby species; burial/smothering of fish eggs/larvae; some species may prefer slight increases in turbidity
Uptake and potential toxicity to benthic invertebrates; possible trophic transfer and bioaccumulation in fish
Behavioural (avoidance or attraction) impacts to electro- or magneto-sensitive fish; could disrupt migration for some species
Implications for larval dispersal/settlement; change in benthic habitat structure and communities; possible smothering of fish eggs/larvae
Creation of new spawning or foraging habitat for some species; artificial reef/fish aggregating effect could redistribute or concentrate local fish stocks; potential for colonization by and range expansion of invasive species
Collision risk and potential for gear entanglement may lead to loss of access for some fisheries; potential marine protected areas; could increase catch rates of target species attracted to the artificial reefs
Hearing specialists (e.g. emerald shiner, brown bullhead); deeper-water nearshore species or offshore species (e.g. lake herring, shortjaw cisco)
Lake trout (loss of spawning habitat); benthic species (e.g. sculpins, burbot, brown bullhead)
Lake trout (egg or fry burial); white crappie (reduced growth); species sensitive to siltation (e.g channel darter); walleye (could benefit)
Top predators (e.g. chinook salmon, lake trout)
Nearshore fishes (e.g. cyprinids); migratory species (e.g., lake sturgeon, American eel, lamprey)
Walleye; lake trout; species sensitive to altered coastal dynamics (e.g. channel darter, eastern sand darter)
Lake trout; lake whitefish; yellow perch; smallmouth bass; dreissenid mussels; round goby
Lake whitefish; lake trout; walleye

Figure 3. Summary of the potential effects of offshore wind power facility-related activities and components on Great Lakes fish and fish habitat (adapted from Hiscock *et al.* 2002).

2. Noise

Based on the relative representation of different effects categories in the literature, of all the potential impacts of offshore wind power projects, noise is likely to prove the most significant to fish behaviour and health over the long term (Simmonds & Dolman 2008). A brief summary of hearing in fish and underwater acoustics is included in Box 2 in order to provide some background and biological context to a discussion of potential impacts of underwater noise from offshore wind power projects on fish.

Box 2: Hearing in fish

All fish species studied to date are able to detect sound, which underwater involves the detection of both sound pressure and particle motion. The detection of sound is fundamental to a fish's perception of its environment. Sound is one of the primary mechanisms through which fish communicate with conspecifics, recognize or perceive auditory signals emitted by prey and predatory species, locate suitable foraging or spawning habitat, and orient themselves. In general, fish use two different sensory systems to detect sound, the inner ear and the lateral line system. While the inner ear functions to detect sounds of higher frequency (>100Hz) over greater distances, the lateral line system allows fish to detect water motion and lower-frequency sound (<100Hz) at shorter distances.

Most fish detect sounds within a fairly narrow range of frequencies or bandwidths; in general from about 30 Hz up to 500-1500 Hz (Popper & Hastings 2009). Species that hear within this range are often referred to as hearing generalists; examples include salmonids and percids. Hearing specialists on the other hand, are able to detect a broader range of sound frequencies, up to 3000-5000 Hz (Slabbekoorn *et al.* 2010); these comprise the majority of freshwater species, and include for example, catfish, carp, minnows, suckers, shiners, dace, chubs, and chubsuckers. Hearing specialists are characterized by a coupling of the swim bladder or other gas-filled chamber to the inner ear, which serves to amplify the energy generated from particle motion, thereby increasing the strength of the sound signal.

Fish species also differ in their hearing threshold, the lowest sound pressure level that they can detect, in units of decibels (dB). It should be noted that underwater dB-levels are different than dB-levels in air given the differences in sound transmission between the two mediums. Owing to its greater molecular density, sound can travel greater distances at higher amplitude levels in water than in air, which has implications for the long-distance impact of noise on aquatic organisms.

The effects of noise on fish have been relatively well-studied. As noisy human activities continue to expand and alter the underwater soundscape, there have been a growing number of studies to assess how fish will respond to these increasing levels of noise. While not exhaustive, Appendix A includes a table summarizing the observed effects and experimental details of sound exposure experiments conducted to assess the impacts of different kinds of noise on a variety of fish species. Generally, the effects of anthropogenic noise on fish can be divided into three categories: physiological effects, behavioural disturbance, and masking.

2.1 Physiological consequences of anthropogenic noise on fish

High impact sounds or sound levels well above those to which fish are normally exposed have the potential to cause physiological damage to the sensory systems of fish, resulting in either temporary changes to hearing abilities (temporary threshold shifts) or even permanent hearing loss (permanent threshold shifts). The type and duration of noise exposure that can cause auditory tissue damage and temporary or permanent threshold shifts in fish are, however, highly variable. Factors such as repetition rate of the sound, sound pressure level, frequency and duration, as well as the hearing sensitivities of individual species and the size and life history stage of the organism, can all affect the potential of various anthropogenic noises to harm or disturb fish.

Laboratory experiments exposing fish to various sound levels have shown that even moderately loud noises are capable of causing considerable temporary shifts in hearing ability (Appendix A). Hearing loss upon exposure to loud sounds is well documented, although in general such threshold shifts appear to be temporary, and the noise levels required to cause hearing loss is highly variable among species. Taken together the studies detailed in Appendix A indicate that knowledge of hearing thresholds is critical to accurately predict the impacts of loud anthropogenic noises on particular species of fish. Certainly, the literature seems to indicate that hearing specialists are more at risk of sustaining hearing loss from anthropogenic noises than hearing generalists. For example, two Great Lakes species, northern pike and lake chub, had temporary hearing loss after being exposed to loud noise from airgun shots, while the broad whitefish, a close relative of the commercially harvested lake whitefish in the Great Lakes, displayed no threshold shift (Popper *et al.* 2005; Song *et al.* 2008). Not surprisingly, another study revealed that lake chub appear particularly sensitive to sound, while broad whitefish are relatively insensitive hearing generalists (Mann *et al.* 2007).

The mechanism for impaired hearing in fish exposed to high pressure sound levels appears to be damage, either temporary or permanent, to auditory tissues. Several studies have documented inner ear damage to fish, in particular to sensory hair cells, in response to sustained or repeated high pressure sounds (Appendix A). While most of these studies have been conducted on tropical freshwater fish and marine species, there is no reason to expect that Great Lakes fishes should be fundamentally different. In one study (McCauley *et al.* 2003), damage from repeated blasts from

an air-gun was still apparent to the inner ear of fish at least two months post-exposure, implying that fish close to high-impact sound sources can sustain permanent threshold shifts in hearing. Indirect effects of hearing loss in fish, whether temporary or permanent, could include increased vulnerability to predators, inability or reduced success in locating prey, inability to communicate with or locate mates, or inability to sense their physical environment (Popper & Hastings 2009).

In addition to causing damage to the inner ear of fish, loud noise has also been shown to injure other non-auditory structures and tissue (Appendix A). For example, several studies using explosives have demonstrated that high sound pressure levels can tear or rupture the swim bladders of fish (reviewed in: Popper & Hastings 2009). As a result, species of fish that have swim bladders or other air-filled cavities are thought to be more prone to damage from high-impact noises than species without these structures (reviewed in: Lewis 1996). Exposure to very loud or high pressure sounds, such as those from explosives, underwater detonation, or seismic airgun blasts, has also been found to cause capillary rupture and internal bleeding, brain damage, and even death among certain fish species (reviewed in: Popper & Hastings 2009; Appendix A). Interestingly, the literature seems to suggest that smaller individuals are generally more susceptible to non-auditory tissue damage than larger fish (Yelverton *et al.* 1975).

Because they are generally stationary or slow moving, there is concern for the early life-history stages of fish in the vicinity of noisy human activities. Fish eggs, larvae and fry have been harmed by the high pressure sounds from seismic surveys (Dalen & Knutsen 1987) and larval and juvenile fish have suffered significant lethal injury and mortality from the sound waves produced by underwater explosions (Govoni *et al.* 2008). Even noise slightly (15 db) above ambient levels has been shown to increase mortality in fish eggs and embryos and reduce growth rates of larval fish (Banner & Hyatt 1973).

Finally, there is evidence that fish exposed to high levels of background noise are at risk of other, sub-lethal health effects such as stress. Various fish species exposed to short-term noise have shown significantly higher levels of blood plasma cortisol (Appendix A), a common hormonal indicator of physiological stress in fish. Other studies report increases in the heart rate of fish exposed to loud noise (Graham & Cooke 2008). As with other environmental stressors, there is the potential for noise-induced stress to affect growth and reproduction in fish (Slabbekoorn *et*

al. 2010), or to increase susceptibility to disease or infection (Popper & Hastings 2009). However, most studies indicate that the noise-induced stress response in fish is transient, with stress levels not tending to be elevated in fish exposed over the long term (Smith *et al.* 2004b; Wysocki *et al.* 2007).

2.2 Behavioural effects of anthropogenic noise on fish

In general, experiments exposing fish to loud noises demonstrate that fish exhibit a freezing or a startle and alarm response at the onset of the novel source of noise (Appendix A). However, most of the studies conducted to assess potential behavioural effects of intense anthropogenic noises on fish have involved the use of pens or cages to hold fish at specific distances from the noise source, thereby impeding the ability of individuals to swim away. If unconstrained, most mobile fish species are expected to elicit an avoidance response and move away from the source of high-impact sounds, in this way reducing the potential for lethal or sub-lethal injury. Field studies which have monitored fish distribution, abundance and catch rates in areas exposed to intense anthropogenic sound levels provide indirect evidence of such avoidance behaviour (Engas *et al.* 1996; Skalski *et al.* 1992; Slotte *et al.* 2004).

While some forms of anthropogenic noise cause avoidance behaviour, low-frequency anthropogenic sounds of low or moderate intensity have also been shown to have an attracting effect on certain fish, especially predatory species, given that they may resemble the sounds produced by hunting fishes (reviewed in: Zucco *et al.*, 2006). Furthermore, there is evidence to suggest that while anthropogenic noise could initially cause fish to avoid an area, certain species might become habituated to modest sound levels after long-term or continuous exposure (Wahlberg & Westerberg 2005).

2.3 Masking effects of anthropogenic noise

Noises that interfere with or mask a fish's ability to detect essential signals and hear biologically relevant sounds could negatively affect normal behaviour, with implications for survival and reproduction (Codarin *et al.* 2009). Furthermore, not only do fish have hearing ability, but most are also able to produce species-specific sounds. For example, fish produce sound in a variety of social situations such as during feeding, aggressive or territorial interactions, or when frightened or to warn off predators. More commonly, sound is produced during courtship and spawning, for

example aiding in mate choice (Verzijden *et al.* 2010) and contributing to the synchronous release of gametes (e.g. Myrberg and Lugli 2006, cited in: Slabbekoorn & Bouton 2008). Fish also rely on their ability to hear sound in order to detect predators and prey, to orient themselves in their underwater environment, and locate suitable habitat.

Most fish emit and detect broadband sound signals within low frequency ranges (i.e. < 500 Hz). Unfortunately, the majority of anthropogenic noises in the underwater environment, such as those produced by motors or machinery, also have their highest energies within the low-frequency range of the sound spectrum. Furthermore, although the very high and potentially damaging sound pressure levels associated with certain human activities are reduced or attenuated over distance from the source, they are often still detectable above ambient noise levels over significant distances in the water column, even up to tens of kilometres from the source (Bailey *et al.* 2010; National Marine Fisheries Service 2010). The result is that background levels of underwater noise within the lower frequency range are elevated enough by human activities to potentially mask hearing in some fish over an extended area, thereby interfering with their communication and orientation signals (e.g. see the study by Simpson *et al.* 2010 where anthropogenic sound altered settlement of fish larvae).

2.4 Noise associated with offshore wind power projects

All phases of the installation and operation of offshore wind power projects are expected to contribute a significant amount of noise to the underwater environment. Concerns over increased levels of these novel sources of anthropogenic noise have prompted a number of recent studies and reviews to assess the potential impacts of wind power project noise on fish physiology and behaviour. The following is a review of the potential impacts of noise generated throughout the life cycle of a wind power project to fish. Fig. 4 summarizes the sound pressure levels associated with various activities occurring throughout the life-cycle of offshore wind power projects, indicating the range in sound levels known to cause behavioural or physiological effects in fish.

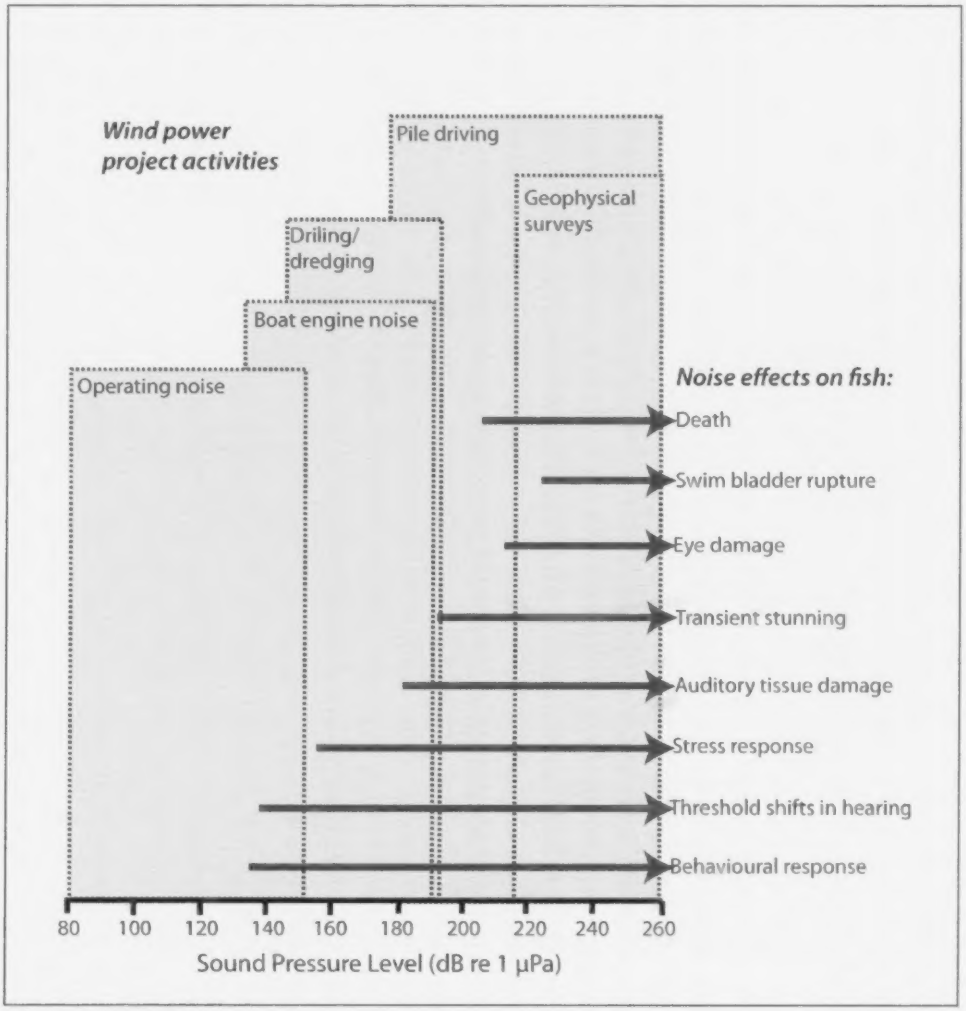


Figure 4. The overlap between levels of underwater noise created by wind power projects and sound levels that affect fish. Measured ranges in source sound pressure levels of various activities associated with wind power project construction and operation are shown (vertical grey rectangles). Superimposed are the threshold sound pressure levels that have resulted in the onset of behavioural or physiological effects in exposed fish (horizontal blue arrows). Minimum threshold sound levels and source sound level ranges derive from the studies tabulated in Appendix A, B and C, as well as those reported in Nedwell & Howell (2004).

Pre-construction phase

During the pre-construction phase, increased underwater noise will be generated by boat traffic in the area, the installation of meteorological masts, and geophysical and geotechnical surveys. Boat noise will be intermittent, and is not likely to have a significant impact on local fish species. Because they tend to be built upon monopile foundations, the installation of meteorological masts will involve pile driving activity, which has the potential to generate significant high-

impact noise levels (see below). However, pile driving activity in the pre-construction phase will be limited to the relatively short time period (days-weeks) required for the installation of individual meteorological mast structures. In contrast, owing to the intense noise levels associated with wind power project related geophysical surveys during the pre-construction and site selection phases, these activities have recently been flagged as an area for concern (Nedwell & Howell 2004). Depending upon the type of equipment used to conduct geophysical surveys (i.e. boomers and sparkers vs. air-gun seismic surveys) there could be significant noise disturbance during these site exploration activities. Empirical studies have yet to demonstrate lethal or sub-lethal effects of boomer or sparker noise on fish but noise from air-guns can clearly cause injury to nearby fish (Appendix A).

Construction phase

The heaviest amount of boat traffic around offshore wind power projects is expected during the construction phase of development, given the number of both small vessels and large, crane- and other equipment-bearing barges required to transport and install the wind turbines. Sound levels and frequencies of boat engine noise types depend upon vessel size, speed and design, with some of the typical source sound ranges reported in Appendix B. While increased shipping noise during turbine installation is not expected to cause direct mortality or injury to fish, there are a number of sub-lethal effects known to arise in fish exposed to sound from vessel traffic. Nearby boating noise can alter the swimming or schooling behaviour of fish (Sara *et al.* 2007), elicit avoidance reactions, interrupt spawning, induce a stress response (reviewed in: Wysocki *et al.* 2006), and reduce auditory sensitivity resulting in acoustic masking (Codarin *et al.* 2009; Scholik & Yan 2002). Thus, there may be significant sublethal physiological disturbance, or behavioural effects to Great Lakes fish in response to even moderate levels of noise from increased boating activity in the wind power project area.

The loudest, most high-intensity sounds associated with offshore wind power projects are expected during the installation of the cables and turbines themselves, and especially during foundation construction. Typical noise levels associated with various construction activities are shown in Appendix B. The installation of the turbine foundations involves dredging, drilling, and pile driving, for example, which together amount to significant noise levels which could cause damage to fish within 100 m (Gill & Kimber 2005). Dredging is required to excavate the

substrate to prepare it for foundation installation (particularly for gravity foundations) and for cable laying, and generates low frequency noise. In addition, the heavy equipment and power tools required for drilling, cutting and welding can also generate very loud noise. While dredging and drilling produce significantly loud source levels of sound underwater, the effects of these activities on fish have not been explicitly explored to date.

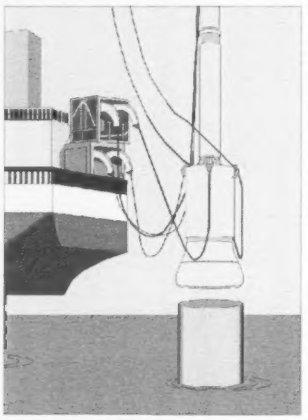
Of all offshore wind turbine construction activities, pile driving (Box 3) in particular is known to produce some of the most intense anthropogenic noise levels in the underwater environment (Bailey *et al.* 2010). Pile driving sounds underwater are characterized by a series of rapid increases and decreases in sound pressure. The sound pressure levels generated by pile driving activity depend on the size and physical properties of both the pile driving hammer and monopile, as well as on the type of sediment into which the foundation is being driven, and the distance from the source. Some of the reported noise levels and sound frequencies of pile driving activity are shown in Appendix B. The high intensity noise generated by pile driving can extend great distances in the water column. For example, measurements of pile driving noise taken during construction of an offshore wind power project near the coast of Scotland showed that received levels were distinguishable above background noise up to 80 km from the source (Bailey *et al.* 2010).

With the exception of underwater explosions, offshore pile driving is one of the only anthropogenic high-intensity sound sources documented to have caused fish kills in the wild (Popper & Hastings 2009). While assessments of potential pile driving effects on fish often extrapolate the findings from studies with other high-impact, impulsive type sounds such as seismic air guns, the inherent differences in the type of sounds generated by these sources make such extrapolations tenuous at best. Though they are still relatively scarce, there have been several recent scientific and grey literature studies (reviewed in: Popper & Hastings 2009 and Snyder & Kaiser 2009) where the authors have tested the impact of pile driving sounds on fish specifically. Among these was an observational study conducted during pile driving for the construction of the San Francisco-Oakland bay bridge, where mortality among several different species of fish was noted within 50 m of a pile. Upon examination, the dead and dying fish were found to have sustained internal bleeding and swim bladder damage (Caltrans 2001).

Box 3: Pile driving activities associated with offshore wind power projects

Large pile drivers are required to ram steel monopile foundations into the sea or lakebed. Strikes are delivered with a pile driving hammer. High impact sound is generated from the strikes (typical source sound pressure levels being ~180-260 dB re 1 µPa @ 1m), with noise levels exceeding background noise levels for many tens of kilometres underwater. Below is an estimate of the pile driving activity required for a typical offshore wind power project. Note that these estimates depend on many factors as outlined below.

Strike interval: **1 second**
Strikes required per monopile: **600-7000**
Installation time per monopile: **Several hours**
Average number of piles completed per day: **1-5**
Duration of pile driving activity for entire wind power project: **Months to a year or more**
Factors affecting installation time/duration of pile driving: **Substrate type (e.g. bedrock vs. sand), size of monopile, number of turbines, weather, availability of necessary equipment**
Example: **Estimate for the Cape Wind project is 8 months of pile driving required for 130 turbines (not including delays due to weather conditions)**



Pile driving hammer installing a steel monopile foundation

A number of additional studies involved holding fish in cages at varying distances from the pile driving sound source, and measuring mortality or specific tissue damage (Appendix C). Several of these studies report increased damage to fish held at closer distances to the pile driving sound source, while others report no damage even among fish held in cages several meters from the piles. It should be noted that several issues with the scientific rigour of these grey literature studies have been highlighted (Popper & Hastings 2009). Regardless, these results demonstrate the importance of pile size and type, strike frequency and duration, the relative sensitivity of different fish species, and especially the distance from the sound source in dictating the relative damage potential of pile driving noise. The U.S. National Marine Fisheries Service proposes that

the area over which physical injury or death of fish from pile driving noise can be expected to extend will be within approximately 9 m of a 24-inch pile, or 18 m of a 72-inch diameter pile (National Marine Fisheries Service 2010). These diameters are much smaller than those typically used for monopile turbine foundations, which would therefore be expected to have a greater impact distance for injury.

The reaction or behavioural thresholds of fish in response to pile driving noise are expected to be breached at lower sound levels than those that would cause physiological damage. As a result, pile driving sounds capable of eliciting behavioural modifications are expected to extend over a greater area from the piles (i.e. approximately 5 km from a 24-inch pile, and up to 10 km from a 72-inch pile; National Marine Fisheries Service 2010). Several technical reports summarize the results of behavioural experiments with various marine fish species and, though they are also subject to some scientific criticism, demonstrate that pile driving activity can elicit startle responses or altered swimming behaviour in nearby fish. However, fish located further away, especially if they are hearing generalists, might not display any observable change in behaviour. Based on these and other studies it is clear that distance from the source is a significant factor in dictating the received sound pressure levels of pile driving activity for fish, and that there is high variability in behavioural reactions between individuals and across species exposed to pile driving noise.

Operational phase

The longest phase in the lifespan of offshore wind power projects is the operational phase. Wind power projects are currently designed to have a 20 to 25 year life-span, meaning that fish will experience a longer period of exposure to wind turbine noise than to any other related noise source. While increased boating traffic may be intermittent during ongoing maintenance work, the majority of the noise associated with the operational phase will arise from the noise generated by the gearbox and the resulting structural vibrations that get transmitted into the water column and substrate via the foundation (Madsen *et al.* 2006). The sound levels and noise frequencies associated with operating wind power projects is strongly dependent upon the size and number of turbines, wind speed (which relates to turbine operating rotation speed) and the foundation type. Typical noise levels and frequencies associated with operating offshore wind turbines are presented in Appendix B. Though these sound levels are not expected to be loud

enough to cause physical damage or hearing loss in nearby fish, they are still detectable above background and could cause avoidance behaviour, or mask acoustic communication in fish.

In a study examining the swimming behaviour of roach and three-spined stickleback in response to played back wind turbine noise, both species were found to react to sound levels between 80-120 dB re 1 µPa (Andersson *et al.* 2007). The roach responded by swimming in sudden bursts, while the stickleback displayed a variety of swimming behaviours including twitching, backing and freezing. These types of swimming patterns are recognized as anti-predator or escape behaviours, and could indicate that the noise was causing stress to the fish.

It has been estimated that certain fish species might only be consistently scared away from the low frequency sounds of wind turbines at distances of less than 4 m, and only when wind speeds are higher than 13m/sec (Wahlberg & Westerberg 2005). Based on the findings of a fish biological survey at the Svante wind farm in Sweden, it was found that European eels did not significantly alter their swimming behaviour when passing a single 220 kW operating turbine at a distance of 500 m (reviewed in: Zucco *et al.* 2006). However, it was reported in the same study that catch rates of cod and roach were halved within 100 m of the turbine during operation, though they were substantially higher in the vicinity of the turbine when the rotor was stopped. This supports the idea that despite general attraction behaviour of fish to artificial structures, certain species might avoid the immediate area of a wind turbine during operation due to the associated low-frequency noise.

Finally, because it falls within the same frequency range as many fish vocalizations, it is thought that the primary impact of operating turbine noise on fish will be a masking effect. It has been shown that the operational noise of wind turbines exceeds background ambient noise over significant distances from the source. Modelled detection distances for three fish species with variable hearing ability indicate that between wind speeds of 8 to 13 m/sec, wind turbine noise is detectable anywhere from 400 m to 25 km away (Wahlberg & Westerberg 2005). Within the zone of detection of wind power noise, it is probable that intraspecific communication will be interfered with or masked, because at the very least wind turbine noise can significantly reduce the distance over which fish are able to communicate (Wahlberg & Westerberg 2005). By masking critical courtship calls, wind turbine noise could make mate detection and spawning

more difficult, if not impossible for some species, with implications for recruitment and population growth. Overall, however, it seems most likely that substantive behavioural or communication disturbance to fish will be limited to high wind speeds at relatively short distances from the turbines.

Decommissioning

The final stage in the lifecycle of offshore wind turbines is decommissioning, though exactly what this process will entail remains unclear. It will likely reflect certain aspects of the installation phase, namely that increased vessel traffic is to be expected, and that heavy cutting tools or machinery may be involved. Thus the effects to fish would be expected to be similar to those described for the installation phase. However, if the monopile or gravity foundations are to be removed completely, this process would probably involve the use of explosives, given that this is the typical mode of removal employed by the oil and gas industry. If this is the case, there could be significant impacts to fish in the area, owing to the high sound pressure levels associated with underwater detonations or blasts. Similar to pile driving, the noise from explosives is known to have a range of effects on nearby fish, from avoidance, to auditory tissue damage and hearing impairment, to swim-bladder or other tissue damage, to mortality (reviewed in: Popper & Hastings 2009). However, the process that will be used in the future to decommission wind turbines in the Great Lakes is unknown, such that predictions of potential effects to fish are still speculative at this point.

2.5 Effects of underwater noise generated from wind power projects in the Great Lakes

Although the majority of studies cited here derive from the marine literature, it is probable that noise generated by wind power projects in the Great Lakes will have a comparable impact upon resident freshwater fish species. Depending on the size of proposed wind power projects, and therefore on the duration of the construction phase, activities associated with the installation of the turbine foundations will likely pose the greatest threat to nearby fish. Most fish are likely to avoid the loud noises associated with areas under construction, which could be detrimental to those species with migratory routes or spawning beds within the sound detection distance of the noise source if the timing of construction overlaps with these critical seasonal occurrences. If construction occurs near the habitat of territorial or slow moving species, or near habitats

housing fish eggs or larvae which are essentially sessile, these will be most at risk of suffering noise-induced stress, physiological damage, or even death.

Hearing specialists are of greater concern for noise impacts from offshore wind power projects than hearing generalists. Within the Great Lakes, hearing specialists include catfish, carp, minnows, suckers, shiners, dace, chubs, and chubsuckers, among others. However, many of these species reside within shallow habitats in the Great Lakes and depending on project location, might not be at high risk of exposure from wind power project noise; one notable exception is the emerald shiner, a pelagic forage fish that is a food source for larger predators such as salmon and trout. Encouragingly, some of the most commercially important species such as lake trout, lake whitefish, and walleye are hearing generalists.

As hearing specialists are at greater risk of noise-induced damage, so too are species with swim-bladders or other air-filled cavities for reasons discussed above. Most Great Lakes fish species possess swim-bladders (including the key commercial species mentioned earlier), which means that the very loud noises associated with certain aspects of wind power projects could be damaging to them at close ranges. Impacts to pelagic schooling species, which also possess swim bladders, might be expected because of their small size and high abundance. The invasive sea lamprey and round goby, however, lack swim bladders, which could mean that they are less at risk from noise-trauma.

3. Electromagnetic fields

In addition to the individual turbines used to harness wind energy in offshore wind power projects, an extensive network of cabling is also required in order to relay the converted electrical energy to onshore power facilities. A grid of inter-turbine cables collect power from individual turbines within the wind turbine array and connect them to transformers, which then transmit the concentrated electrical energy to the mainland via a long cable link. Cabling is run along the sea-floor or lake-bed and is either buried below the sediment in dredged out trenches, or lain atop the substrate in cases where dredging isn't feasible. The transmission of energy from offshore wind power projects has been accomplished using either high-voltage direct current (DC) or alternating current (AC) systems, depending on transmission capacity and distance

offshore. While the industry standard for design of AC cables requires shielding to reduce direct electric field emissions, the magnetic fields generated by the current flow through the cables cannot be effectively shielded, and can therefore still create an induced electric field beyond the cables. As a result, electromagnetic fields (EMFs) are induced in the vicinity of both AC and DC underwater cables, though the strength of these fields may vary depending upon cable type.

Box 4: Electromagnetic field detection in fish

There are two components to electromagnetic field detection in fish: electric field detection and magnetic field detection. All living organisms produce electrical fields. The bioelectric fields generated by aquatic organisms are species-specific, vary in strength and frequency, and comprise both AC and DC components (Eeuwes *et al.* 2008). However, they are generally weak signals of very low frequency. Electroreception is the biological ability to detect and make use of such electrical impulses. Among fish, electroreception has been documented in a number of taxa including eels, lampreys, elasmobranchs (sharks, skates and rays), sturgeons and catfish. Of these, the elasmobranchs and lampreys are thought to possess the greatest sensitivity to electric fields owing to specialized sensory organs or electroreceptors. Many teleost fish also possess a passive electric sense, enabling them to detect the weak bioelectric fields emitted by aquatic organisms. In addition, certain fish species (e.g. eels), employ active electroreception, meaning that they can sense their surroundings by detecting distortions in the electric fields that they emit.

Electroreception is thought to serve a variety of functions in fish. Because it allows fish to sense the weak electric fields of other organisms, electroreception is thought to be involved in prey detection. Behavioural experiments have clearly indicated the importance of electroreception when locating prey (Kalmijn 1971) and also when detecting conspecifics (e.g. Peters *et al.* 1974). A recent study examining the prey detection behaviour of brown bullheads (a catfish species found in the Great Lakes) revealed that these fish responded more to the DC component of bioelectric fields emitted by prey than to AC stimuli (Eeuwes *et al.* 2008). In experiments with adult sea lamprey, weak electric fields were found to elicit reproductive behavioural responses (Chung-Davidson *et al.* 2008). The sensitivity to bioelectric fields is known to be highly variable and species-specific and the electromagnetic capabilities of many species are not known.

Many fish species are also able to detect magnetic fields (Hellinger & Hoffmann 2009; Ohman *et al.* 2007), including the earth's magnetic field (Gill & Kimber 2005; Lohmann & Johnsen 2000). The primary purpose of magnetic field detection in fish is as a cue for geomagnetic orientation, especially while migrating (Lohmann & Johnsen 2000; Ohman *et al.* 2007). Many magneto-sensitive fish possess magnetite particles or ferro-magnetic materials thought to endow them with the ability to detect geomagnetic fields (reviewed in: Formicki *et al.* 2004b and Ohman *et al.* 2007). Species known to have magnetic field perception include elasmobranchs, migratory salmon, eels, tuna, and rainbow trout (reviewed in: Hellinger & Hoffmann 2009 and Ohman *et al.* 2007). A variety of other species could also be magneto-receptive. For example, a recent study in a European lake showed that fyke nets rigged with magnets had significantly higher catch rates (of almost 50%) for a variety of cyprinid and percid species compared to control nets (Formicki *et al.* 2004b).

Various species have been shown to swim towards artificially generated magnetic fields—a behaviour attributed to a possible "curiosity reflex" (Formicki *et al.* 2004b). Similar preference has been noted among the larvae and fry of rainbow trout, which also moved or oriented themselves toward the source of a weak constant magnetic field (Formicki *et al.* 2004a). In contrast, certain species might avoid artificial magnetic fields. For example, in the experiment with magnet mounted fyke nets, eels were the only group of fish that were not found in higher abundance in the magnetic nets than in the control nets (Formicki *et al.* 2004b), possibly indicating an avoidance response. Eels exposed to artificially elevated magnetic field strengths have also been shown to have higher activity levels (Vasilyev & Gleyzer 1973), a behavioural pattern that could imply disturbance by the magnetic field.

Many fish species are able to detect EMFs (Box 4), and effects on fish are expected if the electric and magnetic fields induced around these underwater cables overlap with species-specific sensitivity to them.

3.1 Potential effects of wind power transmission cable EMFs to fish

The strength of the electric field generated by underwater power cables depends on the type of current being generated, the degree of cable insulation, the depth of burial of the cable, and distance from the cable. For example, calculations show that a monopolar DC power transmission line could emit electric fields of 70,000 μV/m at a distance of 1 m from the cable (Koops 2000), with weak electric fields of 100 μV/m occurring up to 10 km away (Matthäus 1995). The induced electric fields from submarine AC cables with perfect shielding and buried to a depth of 1 m, on the other hand, would be much less: around 90 μV/m at a 1 m distance, and 10 μV/m at 8 m away (CMACS 2003).

The detection distance of induced electric fields from underwater cables is dependent upon the electrosensitivity of nearby fish species. The lowest threshold for detection of electric fields among teleost fish is assumed to be around 7,000 μV/m, with behavioural thresholds reported for electric field strengths of 500,000-7,500,000 μV/m (Poléo 2001). Electric fields of these strengths are likely only to occur very near the cables, meaning that the detection distance for most fish will be small. Highly sensitive species (e.g. lampreys, eels) will be able to detect electric fields at further distances (CMACS 2003; Poléo 2001).

Depending upon the strength of the electric fields induced around underwater cables associated with wind power projects, electrosensitive fish could either be attracted or repelled by them (e.g. Gill & Taylor 2001; Kalmijn 1982; Marra 1989), leading either to congregation or dispersal of these species within areas of high cable density (Gill 2005). Because electric fields are used by some fish for prey detection, spatial orientation and possibly navigation, anthropogenic introduction of EMFs in the aquatic environment has the potential to result in poor hunting performance, disorientation, or failure to complete migrations (Wilson *et al.* 2010).

There is even less known about whether the magnetic fields generated by wind power project cabling will attract or repel fish. Certainly, the magnetic fields emitted from some types of

electric cables have strengths similar in magnitude to the earth's magnetic field, and are detectable by aquatic organisms up to several meters away (Gill 2005). While exposure to constant artificial magnetic fields can have physiological effects on fish, including hormonal effects, slower embryonic development, reduced biomass, and increased mortality (reviewed in: Ohman *et al.* 2007), the most likely impacts of human-induced magnetic fluxes are expected to be temporary (i.e. while fish move through the area) and behavioural. For species that rely on Earth's magnetic field during migration, artificial magnetic fields from wind turbine cabling could interfere with their orientation and navigation, potentially redirecting or delaying migration (Ohman *et al.* 2007). Slower swimming speed among migrating eels has been reported in the vicinity of an offshore wind power project (Westerberg & Lagenfelt 2008) but to our knowledge, no experiments have conclusively demonstrated whether magnetic fields generated by wind turbine cabling has impacted fish migration.

Differentiating between the responses of fish to magnetic stimuli as opposed to the electric fields produced by underwater power cables is difficult, as both are components of the electromagnetic fields that they generate. Furthermore, some of the most electrosensitive species are also magneto-sensitive, meaning that they may be able to detect and respond to both components of EMFs. Other species might only be sensitive to a single component of EMFs. A recent technical report highlighted the results of a study in which the investigators evaluated the response of fish to EMFs with similar characteristics and magnitude to those associated with offshore wind power project cables (Gill *et al.* 2009). The authors found evidence that benthic elasmobranchs responded to EMF exposure, with an indication of attraction to the cables, though the response was variable among individuals and species. Based on the responses of these fish, however, they predict that electromagnetic-sensitive species may encounter EMFs at or above their lower detection limits up to 295 m from a cable.

3.2 Potential effects of EMFs generated by offshore wind power projects in the Great Lakes

Electromagnetic fields will be generated by underwater transmission cables associated with offshore wind power projects in the Great Lakes throughout their operational lifetime. Not only will these cables exist in relatively high concentrations within the offshore wind power project area, but long cables connecting the turbine array to the shore will also generate EMFs along the

transecting line, with the potential to impact shallow-water species as well. Because cables will be laid along or below the lake bottom, demersal (i.e. bottom-dwelling) fish might be more affected by the emitted EMFs than pelagic species by virtue of greater proximity of the former to the source of the electric and magnetic fields. In addition, electro- and magneto-sensitive species will be more affected by EMFs than species that are unable to detect electric or magnetic fields. Much of the research on the impacts of wind power projects to EMFs has focused on the highly electro- and magneto-sensitive elasmobranchs, a group that doesn't exist in the Great Lakes. However, other electrosensitive taxa known to inhabit the Great Lakes include lampreys, catfishes, and lake sturgeon. A number of known magneto-sensitive species also reside in the Great Lakes including migratory species like the American eel, rainbow trout, and chinook, sockeye, and chum salmon. Based on the European study with fyke nets (Formicki *et al.* 2004b) which demonstrated magneto-reception in perch and pike, the Great Lakes relatives of these species may also be able to detect magnetic fields.

Of the Great Lakes species sensitive to electromagnetic fields, the American eel and lake sturgeon pose a particular concern when it comes to potential impacts from offshore wind power projects. Both species have undergone large reductions in abundance over the past century and are of conservation concern in Ontario and the Great Lakes basin. Both are also highly migratory, explaining their need for electromagnetic detection capabilities. Sexually mature, silver-phase American eels migrate from Lake Ontario into the Saint Lawrence on their way to spawn in the Sargasso Sea; the larvae that have metamorphosed into the glass eel and then elver stage subsequently pass through this same corridor on their way to Lake Ontario tributaries. Lake sturgeon migrate upstream into Great Lakes tributaries to spawn in the spring. Electromagnetic cables passing through the migration corridors could therefore have the potential to alter the migratory patterns or routes of these two species.

Based on what is currently known from the literature, it appears unlikely that EMFs from underwater cables will have any acute, physiological effects on adult Great Lakes fish. There is, however, evidence to suggest that the EMFs emitted from transmission cables might attract or repel sensitive species to the cables, which could result in a redistribution of species within the detection distance of the EMFs. Finally, an area that should be further explored is the potential effect that EMFs could have on early development and embryogenesis in fish. While very few

studies have been published, exposure to EMFs during embryogenesis was found to decrease body lengths and weights, change the number of vertebrae, and increase the morphological diversity of juvenile roach (Chebotareva *et al.* 2007), and delay embryogenesis and development in fertilized Medaka fish eggs (Cameron *et al.* 1985). While significant, these findings would only raise concern if fish are likely to lay their eggs in the immediate vicinity of submarine cabling, where the EMF strength would be comparable to experimental exposure values.

4. Alteration of current and wave strength or direction

The physical presence of subsurface structures such as wind turbine towers and foundations necessarily alters the flow of water around them (Fig. 5). Changes in the strength or direction of currents and waves resulting from these physical obstructions can affect local hydrographic conditions around and between turbines within a wind power project, with potential effects extending downstream as well. In general, currents and water flow are accelerated in the immediate surrounding area of a physical obstruction, while mean current velocity and wave energy could be attenuated by diffraction or interference downstream of the wind power project (Hiscock *et al.* 2002).

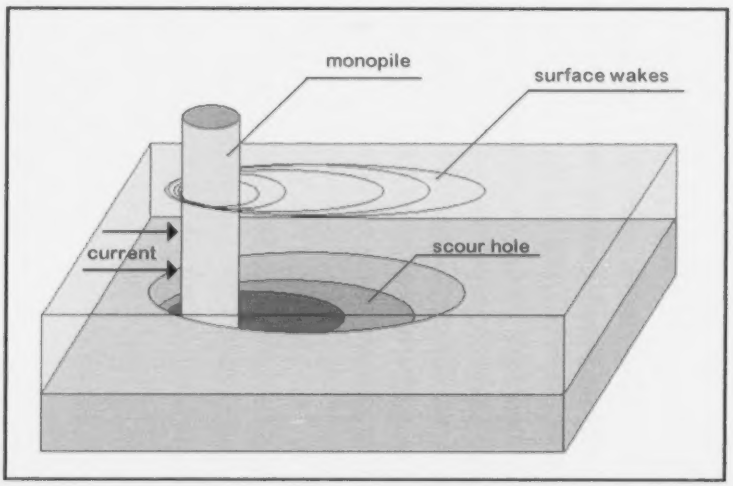


Figure 5. Depiction of local scour around a cylindrical element, like a monopile, showing the scour hole that develops in the absence of scour protection as a result of altered current dynamics around the structure.

Changes in local water movement patterns could alter the distribution or dispersal patterns of various life stages of fish within or downstream of a wind power project (Gill 2005). For example, flow rates can determine the settlement rates of juvenile reef fish (Breitburg *et al.* 1995; Snelgrove & Butman 1994), water currents are known to play a significant role in the sensory processing of fish (Montgomery *et al.* 2000), and certain species, such as walleye, are thought to follow currents during annual migrations (Great Lakes Fishery Commission 2009). As a result, changes in local current strength and direction could have implications for fish within the area of hydrographic impact of wind power projects. The degree to which local changes in current regimes might influence fish movement or behaviour is unclear. However, the biological impacts arising from wind turbine-induced changes to hydrography or hydrodynamics are likely to be confined to the local scale, and by most accounts are expected to be minimal (Hammar *et al.* 2010).

The change in water flow around the turbine structure also increases water column turbulence in the vicinity of the tower. This could lead to an increase in suspended sediment and turbidity nearby, with potential impacts to fish foraging or health (see Turbidity section below) but it could also be of consequence if the turbines are installed in areas that are typically stratified. If so, the resultant increase in water column mixing could weaken the strength of stratification (Hammar *et al.* 2010) and change the physical (i.e. temperature) and chemical (i.e. salinity or dissolved oxygen) nature of the surrounding water, which could impact the vertical movement or distribution of nearby aquatic species (Boehlert & Gill 2010). However, calculations for a chemically stratified water body indicate that even where an array of 30 monopile foundations located within a 20 km^2 area was established, the increase in water turbulence would only cause a 1% increase in mixing above background levels, which is considered insignificant (Karlsson *et al.* 2006 cited in: Hammar *et al.* 2010).

5. Sediment transport and deposition

The increase in current velocity and change in water flow around turbine foundations alters local sediment transport dynamics, resulting in scour and substrate loss around the base (Fig. 5). In general, this means that finer sediments are swept away from the base and redistributed downstream, leaving only the coarser and heavier sediments within the scour pit. In contrast, the

subsequent leeward deposition of suspended sediments could result in shoaling and a shift to finer-grained sediment particle size further away from the turbines. These far-field effects could alter natural coastal processes like sediment erosion and deposition, especially along dynamic shorelines with sandy shoals or beaches. This is of potential concern because those areas can provide critical habitat for some fish species, including several species at risk in Ontario which appear highly sensitive to habitat disturbance from shoreline modifications that increase siltation and sediment loading (e.g. eastern sand darter, channel darter, silver chub). Within the Great Lakes, fish species that utilize the dynamic beach habitat of Lake Erie's northern shore (e.g., around Long Point and Point Pelee) might be particularly prone to alterations in coastal engineering processes; for example, declines in the range of channel darter along the north shore have been linked to the effects of shoreline modification on beaches (Reid & Mandrak 2008).

The extent of scour around a wind turbine foundation is highly dependent upon the strength of current or wave energy acting upon it, the nature of the surrounding substrate, and the shape and size of the foundation itself (Besio & Losada 2008). Modelling studies estimate that the area around a structure prone to scour is approximately ten times the diameter of the structure, which has been confirmed by field measurements as well (Baker 2003). In order to counteract the loss of sediment and mitigate potential impacts to foundation stability, scour-protection materials (Fig. 2) are generally installed at the base of offshore structures with radii extending anywhere from 10 m (Wilson & Elliott 2009) up to 25 m or more (Baker 2003). However, secondary scour is still possible even with these materials in place (Rees *et al.* 2006).

It is possible that an array of wind turbines will cause a cumulative increase in general or global scour around the wind power project area or result in increased far-field sediment deposition downstream (Besio & Losada 2008). Thus, the installation of wind turbines could lead to large-scale changes in hydrography and sea-bed morphology in some areas (van der Veen *et al.* 2008). The likelihood of cumulative hydrographic disturbance will depend, among other factors, on the distance between the turbines. A suggested distance of >300 m between monopiles (Department of Trade and Industry 2000) is believed to be sufficient to ensure that any wake effects generated by each pile will not interact with each other, thereby minimizing global scour effects.

By altering the size distribution of sediment particles around tower foundations, scour processes arising from hydrographic changes could have significant impacts on the physical structure of adjacent habitats for benthic fish and invertebrates. The distribution of sediment particle size within benthic habitats is a strong determinant of the identity and diversity of their associated species assemblages (Culp *et al.* 1983; McBreen *et al.* 2008; Rempel *et al.* 2000). As a result, benthic communities adjacent to wind turbines are expected to be most impacted by altered sedimentation rates and scouring.

Increased sediment dispersal around the turbine foundations could also degrade spawning habitat or increase egg and larval mortality as a result of burial or smothering by drifting or re-deposited fine-grain sediments (Shackle *et al.* 1999; Wilson *et al.* 2010). Great Lakes species likely to deposit eggs within the area occupied by an offshore wind power project could include yellow perch, walleye, lake whitefish and lake trout, which is worrisome because the latter species is already suffering from depressed spawning success in almost all areas of the Great Lakes. Increased sedimentation has been shown to reduce spawning and egg incubation success in yellow perch (Thorpe 1977) and lake whitefish (Fudge & Bodaly 1984), while increased silt deposition resulted in significant mortality of northern pike embryos (Hassler 1970).

6. Changes in water quality

6.1 Turbidity

Significant, though temporary, increases in suspended sediment will result from dredging and drilling operations during the construction and installation of wind turbine foundations and the trenching and laying of transmission cables. In addition, hydrographic disturbances and scour processes arising from the physical presence of turbine structures during the operational lifetime of offshore wind power projects can increase nearby concentrations of suspended sediment and increase local turbidity on a longer time scale, though on a smaller spatial scale.

Increased turbidity reduces visibility in the water column, resulting in reduced feeding or foraging ability among larval and juvenile fish (Engell-Sørensen & Skyt 2001; Johnston 1981), as well as for some adult visual predators such as the muskellunge (Miller & Menzel 1986).

Among Great Lakes species, reduced growth rates in response to increases in suspended solids have been documented for white crappie, channel catfish, coho salmon, rainbow trout, brook trout, and largemouth bass (reviewed in: Kerr 1995). Not all fish species will be impacted in the same way, however. Walleye, for example, are adapted to more turbid waters than some other Great Lakes fish species and could benefit from slight increases in turbidity. Coarse suspended particles can also harm fish through the physical abrasion of the body surface and destruction of the protective mucus layer, which could result in increased susceptibility to disease or parasites (Everhart & Duchrow 1970). Furthermore, high levels of suspended sediment can clog a fish's gill filaments and lead to suffocation and death (Johnston 1981).

Plumes of turbid water can also cause physiological stress in fish (Bash *et al.* 2001; Waters 1995). Consequently, the initial behavioural response of most adult fish to turbidity is avoidance (Engell-Sørensen & Skyt 2001; Kerr 1995). Generally fish larvae are more susceptible to lethal and sublethal effects of suspended sediment than fish eggs of the same species, though both life history stages are more sensitive than adult fish. As a result, there could be significant negative impacts from turbidity on fish eggs and larvae in the area, as well to benthic invertebrates whose respiratory structures can be damaged by increased concentrations of suspended sediment. However, the most significant increases in turbidity are expected during the construction phase when dredging and pile driving takes place, and will therefore be temporary, though potentially widespread.

6.2 Release of sediment-bound contaminants

Dredging and sediment re-suspension could also threaten fish health given the potential for remobilization of sediment-bound contaminants. Fine-grained sediments have a strong capacity to bind heavy metals and persistent organic pollutants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and organochlorine pesticides including DDT. These contaminants bind rapidly to particulate matter in the water column and subsequently settle out into the sediment. As a result, sediments act as a sink for persistent organic and heavy metal contaminants.

Despite recent bans and decreased production of some of the more harmful chemical compounds, several hundreds of years of intensive industrial and agricultural activity within the Great Lakes

region have left a legacy of accumulated contamination within lake sediments. Recent, extensive lake-wide sediment surveys have revealed that elevated levels of PCBs, organochlorine pesticides and heavy metals including mercury, arsenic and lead still exist in the sediments of all of the Great Lakes (Marvin *et al.* 2004a; Marvin *et al.* 2004b). Among the Great Lakes, Lake Ontario and the western basin of Lake Erie have the highest levels of sediment contamination, with concentrations of organic contaminants and heavy metals exceeding the strictest Canadian Federal and Ontario Provincial guidelines for sediment quality at numerous sites (Marvin *et al.* 2003; Marvin *et al.* 2004c). Some areas are so heavily contaminated that they have been designated as Great Lakes Areas of Concern under the U.S.-Canadian Great Lakes Water Quality Agreement.

The presence of persistent organic or heavy metal pollutants can adversely affect Great Lakes wildlife, including fish. Even though these contaminants are largely contained within the sediment, disturbance due to anthropogenic activity can re-suspend these sediments and remobilize contaminants within the water column where they become bioavailable. As a result, sites impacted by historical contamination can still pose a significant hazard to aquatic organisms. Monitoring studies of recently dredged sites in marine areas known to have contaminated sediments found large increases in the accumulation of metals in the tissues of filter feeders (Hedge *et al.* 2009), as well as dramatic reductions in recruitment rates of sessile invertebrates after dredging (Knott *et al.* 2009). These and other similar studies demonstrate the potential for dredging activities to release historical contaminants from the sediment and cause significant increases in water column contamination, resulting in uptake and accumulation by aquatic organisms. Given the chemical nature of these types of contaminants, they also have a propensity for biomagnification, increasing in concentration up the food chain and resulting in high levels of contamination in larger fish species.

Owing to high levels of sediment contamination in many areas of the Great Lakes, often much higher than in coastal marine sediments, there is a greater concern over the release of sediment-bound contaminants during the construction of offshore wind power projects in the Great Lakes than in the marine environment. Dredging, pile driving and cable trenching activities all have the potential to cause significant disturbance to lake sediments which could result in the remobilization and increased bioavailability of harmful environmental contaminants. Although

disturbance will be temporary, being limited to the foundation installation and construction phase, there could be widespread and long-lived consequences if there is uptake and trophic transfer among nearby aquatic organisms.

6.3 Other water quality issues

In locations where the substrate composition requires that monopile foundations be part-drilled into the lake-bed, water quality issues associated with the evolution and discharge of drill cuttings and other waste products could arise. Drill cuttings include fine grained particles of the underlying geological substrate that are generated in the bore-hole by the action of drilling into subsurface geology which then get dispersed around the area of the hole—resulting in increased turbidity and the associated biological effects discussed above. In addition, these dispersed cuttings could also contain traces of drilling fluids, which are used to lubricate and cool the drill bit and to carry or pump the rock or drill cuttings excavated by the drill bit up to the surface and out of the bore hole.

Depending on the nature of the drilling fluid—whether it is a water-based mud or a synthetic or oil-based mud—there could be contamination effects and chemical poisoning upon dispersal into the nearby aquatic environment (Punt *et al.* 2009). Organic-phase or oil-based drilling fluids have been identified as potential sources of hydrocarbon and other contaminant release and toxicity, at least in the marine environment where they have been used in drilling for oil and gas exploration (OSPAR Commission 2009). Generally, however, the environmental effects related to drill cuttings are depositional effects related to habitat smothering by the fine-grained particles (Wilson *et al.* 2010). As a result, benthic organisms are most impacted by the deposition of drill cuttings, although associated biological effects do not normally extend beyond 500 m from drilling platforms (Hurley & Ellis 2004). The drilling process might also result in thermal impacts to the nearby water column, as the produced water will be warmer and less dense than the receiving water. This could cause thermal shock to zooplankton and fish larvae in the immediate vicinity of the outfall (Canada-Newfoundland Labrador Offshore Petroleum Board 2008), though such effects would likely be short-lived.

During the construction and operational phases of offshore wind power projects, there is also the potential for the accidental release of environmental contaminants. Wind power projects

represent potential collision hazards for vessels, and although such collisions are unlikely, they could result in significant impacts to the local aquatic environment if shipboard wastes, oils or fuels are subsequently released. Hydrocarbon spills are known to have toxic effects on aquatic organisms, and can affect local abundance and diversity, especially of planktonic organisms which represent the food base of many fish species. While mobile species and life history stages generally avoid a hydrocarbon spill by moving away, less mobile invertebrates and fish eggs and larvae could suffer chronic or acute toxicity from hydrocarbon exposure (Canada-Newfoundland and Labrador Offshore Petroleum Board 2008).

In addition to the possibility of spills resulting from vessel collisions, hydraulic or other operating fluids could leak from damaged turbine units or be accidentally discharged during routine maintenance or servicing, also with potential lethal or sublethal effects on local fauna. Finally, the use of anti-fouling paints on turbine structures and subsequent leaching into the aquatic environment is likely to cause adverse effects on nearby organisms. Paints containing copper or tributyl-tin compounds, for example, are designed to cause chronic or acute toxicity in invertebrates. Although wind power development is unlikely to cause significant chemical contamination, accidental discharges, spills and leaching could have serious negative environmental impacts.

7. Habitat loss

During the construction phase, the installation of turbine foundations and the trenching and laying of submarine cables will necessarily destroy or remove the previously existing original benthic habitat, along with any sessile flora or fauna within the area of impact. In addition, mobile benthic organisms in the area will be displaced, though they could relocate to other nearby areas with suitable habitat. Benthic fishes (e.g. sculpins, catfishes, lake sturgeon and burbot) and species with benthic-associated spawning (e.g. lake trout, lake whitefish, and walleye) or larvae and juveniles that settle into and inhabit benthic habitats (e.g. lake trout, sculpins) are likely to be most vulnerable to disruption from habitat loss during project installation.

The extent of benthic habitat lost due to the physical presence of wind turbine-associated installations will depend on the number of turbines within a facility (and therefore on the concentration of inner-array cables), foundation type (with gravity base foundations occupying larger areas than monopile foundations), and on the type and extent of scour protection placed around the foundation bases. However, the actual physical area of the lake- or seabed covered by project facilities is generally expected to be less than one percent of the total project area (Petersen & Malm 2006). For the Cape Wind Energy Project off the eastern coast of the United States, which would house 130 turbines, it is estimated that only 0.12-0.35% of the total project area will be occupied by turbines, cables and scour protection (MMS 2009). Thus, the amount of benthic habitat destroyed as a direct result of the presence of project facilities would be considered small and, so long as the structures are not built upon rare habitats or species, most likely negligible (Petersen & Malm 2006).

Disturbance to lake bed sediments resulting from dredging and cable trenching activities will also temporarily impact benthic habitat. The area of impact during the construction phase will be greater than the area occupied by the physical structures themselves. According to the Environmental Impact Assessment for the Cape Wind project, for example, it is anticipated that 5% of the total project area will be disturbed during the construction phase (MMS 2009). In cases where the inner-array cables and transmission lines will be buried or laid in trenches, significant disturbance to nearby sediment and benthic communities is expected. Whether they are buried directly or allowed to backfill through natural sedimentation processes, the newly dredged or water-jetted trenches will alter the nearby benthic habitat.

Monitoring studies have shown that recently dredged areas differ significantly from reference sites, often having reduced abundance and richness of benthic fauna (Cooper *et al.* 2008; Smith *et al.* 2006). Re-colonization rates and the degree of taxonomic and functional recovery of recently disturbed areas are variable, but could take months to years for natural succession processes to re-establish pre-disturbance communities (Gill 2005). Thus, while disturbance to the benthic environment during construction might be temporary in nature, there could be longer-term consequences to nearby benthic habitats and communities. In addition, there could be significant indirect alterations or loss of benthic habitats within the wind power project area

during the operational phase via modifications in hydrodynamics and changes in sediment composition that result in localized scour and deposition as discussed above.

8. Habitat creation

While the installation of wind turbine foundations and the addition of scour protecting revetments around their bases will destroy the original benthic habitat upon which they are built, these structures will also create new habitat and ultimately lead to a net gain in habitat availability in the area. For typical monopile foundations with scour protecting materials extending a standard 10 m radius out from the base, it has been calculated that the net amount of habitat created can be up to 2.5 times the area lost (Wilson & Elliott 2009). Because monopiles are typically installed in areas with soft or sandy substrates, the habitat created by the installation of turbines and scour protection will necessarily differ in character to the type of habitat lost. That is, the introduction of new hard substrates will change the original 2-dimensional substrate to a more complex 3-dimensional habitat space (e.g. see Fig. 2).

The presence of vertical structures in the water column and rocky reef-like scour protecting materials on the lake-bed, especially in areas characterized by soft or sandy substrate, increases local habitat heterogeneity and could potentially enhance the abundance and diversity of organisms nearby. It has been recognized by limnologists and marine ecologists alike that hard-bottomed substrates are often disproportionately important habitats, in contrast to unconsolidated, soft substrates (Janssen *et al.* 2005). Not only would new hard-bottom structures provide ideal habitat for colonization by epibiotic or fouling communities (i.e. organisms commonly found attached to man-made structures such as docks, boats, pilings etc.) but they also have significant potential to create novel habitat for motile invertebrates and fish species.

8.1 Colonization by invertebrates

One of the most limited resources for epibiotic organisms that require hard substratum is available space on which to settle and grow (Sheehy & Vik 2010). The hard substrate extending up into the water column from wind turbine foundations have large amounts of surface area exposed to local currents and therefore represent ideal habitat for epibiotic communities (Sheehy & Vik 2010). Thus, depending on the timing of construction and availability of larvae in the area

(Hiscock *et al.* 2002), this novel type of substrate would be expected to be readily colonized by a diverse and abundant invertebrate fauna, as has been demonstrated on wind turbine foundations in the marine environment. However, it should be noted that compared to the marine environment a much smaller pool of organisms available for colonization of artificial structures exist in north temperate freshwater ecosystems (Gannon 1990). Hard substrates in freshwater environments are generally much more sparsely colonized by encrusting plants and animals than similar structures in the marine environment. Nonetheless, introduced hard substrates in freshwater ecosystems have been shown to effectively enhance habitat availability for many species. For example, the construction of a rubble-mound breakwater in western Lake Erie provided suitable habitat for periphyton (*Cladophora*) and resulted in a more diverse assemblage of macrozoobenthos than nearby sandy substrates (Manny 1995).

The development of fouling communities on the below-water surface of the towers as well as upon the boulder, or rip-rap scour protecting materials will be dictated by ecological processes of succession, competition, and predation, as well as by the chemical composition and physical relief of the structures (Petersen & Malm 2006). While knowledge and experience of fouling communities on similar structures in comparable environments can suggest how new substrates will be colonized, site specific variables make detailed predictions about what exactly these communities will look like difficult (Linley *et al.* 2007). Offshore wind power projects provide atypical substrates for fouling, being constructed at different depth ranges and orientations, and of materials with different textures than naturally occurring hard substrates (Wilhelmsson & Malm 2008). As a result, they might not necessarily support the same species assemblages that are found on nearby natural hard substrates.

Surface texture is a strong determinant of the associated fouling community that develops on vertical substrates (Petersen & Malm 2006). A study comparing steel and concrete pilings found that significantly different epibenthic assemblages colonized the two types of vertical structures, with preference for the different material types being species-specific (Andersson *et al.* 2009). Macroinvertebrate colonization of novel benthic substrates, on the other hand, is strongly influenced by substrate heterogeneity and surface complexity, as well as by the size and distribution of interstitial spaces (Ward 1992). In a study comparing two types of materials used in shoreline engineering projects in Wisconsin lakes, it was demonstrated that materials with

more complex bottom structures supported a greater abundance and taxa richness of macroinvertebrates (Schmude *et al.* 1998). Evidently the type and size distribution of materials employed in the construction of turbines and installation of scour protection, respectively, will have a strong influence on the nature of the invertebrate communities that utilize the new habitat.

Once the encrusting community is established upon the new hard substrates provided by wind power structures, further colonization by mobile forms which live within the microhabitat created by sessile organisms or their off-cast shells can also occur. The epibiotic communities that develop on artificial structures are often dominated by filter-feeding organisms (Wilhelmsson & Malm 2008) which can profoundly alter local ecosystem dynamics by concentrating energy and food resources from planktonic and pelagic producers and making it available to predatory fish in the area (Sheehy & Vik 2010). In addition, owing to the physical effect of the structures on local hydrodynamics, complex artificial structures tend to trap drifting organic material and promote the local accumulation of dead animal and plant material (Falcao *et al.* 2009). In this way, artificial structures act as a localized sink for organic matter and nutrients which in turn favours increases in local production, thereby supporting increased abundance of macroinvertebrates (reviewed in: Smokorowski & Pratt 2007) and enhancing the fish forage base near the wind turbine foundations.

8.2 Habitat for fish species

In addition to providing ideal habitat for colonization by aquatic invertebrates, wind turbine structures—and especially the rocky reef-like scour protection placed around them—might also create new habitat for a variety of Great Lakes fish species. In the marine environment, the presence of offshore wind turbines (Wilhelmsson *et al.* 2006a; Wilhelmsson *et al.* 2006b) and other renewable energy devices (Langhamer & Wilhelmsson 2009; Langhamer *et al.* 2009) has been correlated with higher average abundances and a greater diversity of fish species nearby than at otherwise featureless, soft-bottomed control sites. The potential benefits to local fish communities by the creation of interstitial refuge and vertical relief, as well as the increased structural diversity of habitat offered by wind turbine structures in the offshore environment has recently emerged as a key topic of discussion in promoting offshore renewable energy devices (Langhamer & Wilhelmsson 2009).

It has long been recognized that the presence of structurally complex artificial structures in the aquatic environment is often correlated with a much greater number and variety of fish species, a phenomenon referred to as the reef effect. It has also commonly been observed that in otherwise structure-less open-water pelagic environments, the presence of floating or artificial water column structures tend to attract aggregations of fish around them. It is thought that such structures serve as visual cues or reference markers for spatial orientation in fish (Langhamer & Wilhelmsson 2009) and provide meeting grounds by increasing the chance of encounters between conspecifics, according to the so-called meeting point hypothesis (Soria *et al.* 2009). Structurally complex habitats are also known to provide refuge, decrease predation risk and enhance foraging opportunities for small or juvenile fish (reviewed in: Smokorowski & Pratt 2007). Availability of shelter from predation is a critical selective feature of complex habitat structures, especially for juvenile and larval fish whose early survival is directly influenced by predator avoidance (Leitao *et al.* 2008). Artificial structures might also provide ambush cover for fish predators as they await prey species and could enhance local fish abundance or biomass owing to increased foraging opportunities.

Correlational evidence suggests that areas characterized by fine substrates like sand and mud have comparatively low value as fish habitat, demonstrated by the fact that these areas typically have the lowest fish abundance and diversity of any habitat type (reviewed in: Smokorowski & Pratt 2007). In contrast, areas with structurally complex substrates generally have higher fish density and species richness, and possess distinct fish assemblages in north temperate lakes, implying that these habitats are important for maintaining lake-wide diversity (reviewed in: Smokorowski & Pratt 2007). Some Great Lakes fish species known to be strongly associated with cobble and rocky substrates, for example, include mottled and slimy sculpins, yellow perch, burbot, lake trout, smallmouth bass, and rock bass (Creque *et al.* 2006; Janssen *et al.* 2005).

By providing higher quality habitat, complex substrates could also indirectly benefit fish fitness. For example, growth rates of yellow and white perch in Lake Ontario were greater for those individuals caught over cobble/rubble shoals than those captured at sandy sites (Danehy *et al.* 1991). In addition, rocky substrates are believed to be the preferred spawning habitat for many fish species, including a significant proportion of fish in the Great Lakes (Lane *et al.* 1996). Examples of commercially or ecologically important Great Lakes species that utilize rocky reefs

or shoal habitats for spawning include lake trout, lake whitefish and walleye, among others (Liskauskas *et al.* 2007). For many lake-dwelling fish species in Canada, the availability of complex substrate is believed to be critical for the successful spawning and early survival of juveniles who use these nursery habitats (reviewed in: Smokorowski & Pratt 2007).

Because artificial structures are known to attract aggregations of fish, the construction and deployment of so-called artificial reefs or fish aggregating devices has been widely adopted as a tool to manage and enhance local fisheries in both the marine and freshwater environments. However, the contentious issue of whether artificial reefs actually enhance fishery biomass or merely serve to aggregate fish stocks from nearby areas remains unresolved. In theory, artificial reefs should only increase fish biomass where habitat, food or other resources are limited for a given species (Leitao *et al.* 2008). The hard substrate provided by wind turbine foundations and scour protecting materials may be thought of as secondary or incidental artificial reefs (Gannon 1990). Thus, in order to understand how these novel habitat structures might affect local fish populations in the Great Lakes, a review of the current state of knowledge related to existing artificial reef structures in the Great Lakes is essential.

Over the past several decades, a number of artificial reefs have been installed in the Great Lakes with the express purpose of concentrating and increasing catch rates of target species for local recreational fisheries, or for enhancing spawning habitat for certain species (Box 5). For example, much effort has been focussed on restoring self-sustaining lake trout populations in the Great Lakes. Depressed reproduction in lake trout is thought to be attributed in part to degraded spawning habitat, resulting from altered land use practices and increases in fine sediments which fill interstitial spaces in natural rocky reefs and smother eggs and larvae. Furthermore, stone hooking schooners which actively collected stone from the lake bottom for construction purposes in the 19th century essentially removed all cobble substrate between Hamilton and Toronto, eliminating at least four lake trout spawning reefs in Lake Ontario (Whillans 1979). In attempts to enhance or restore naturally reproducing populations of lake trout in the Great Lakes, artificial reefs have been constructed as early as the 1950s, with at least some indications of success (Fitzsimons 1996).

Artificial reefs in the Great Lakes can successfully attract various species of fish, including targeted sport fish for local anglers, and also potentially increase spawning habitat for reproductively struggling species like lake trout (Box 5). Depending on location, depth, foundation type, and on the size and composition of scour-protecting materials used in wind turbine installations, offshore wind power projects in the Great Lakes may well function as incidental artificial reefs with similar effects on local fish populations as those built expressly to create new habitat. In this way, the introduction of novel hard substrata to soft-bottomed areas of the Great Lakes could increase habitat availability and benefit various species of fish. However, it remains unclear as to whether such structures could enhance fish production or whether they would simply attract fish from nearby populations, resulting in depleted stocks elsewhere.

Box 5: Artificial reefs in the Great Lakes: examples and lessons learned

Tawas artificial reef in Saginaw Bay, Lake Huron: This reef was constructed in 1987 to create suitable spawning habitat for lake trout and other species, as well as to improve local angling success by attracting desirable fish species. Post-construction gill netting and underwater video recordings the following fall revealed that lake trout began congregating around the reef area in significantly higher numbers than in the surrounding sand flats. In addition, fry traps collected in the spring were found to contain live lake trout and lake whitefish fry, while yearly egg trap monitoring revealed consistent numbers of lake trout eggs at the artificial reef every year (Foster & Kennedy 1995). This represents one of the only cases where evidence of lake trout spawning has been noted at artificial reefs in the Great Lakes (Fitzsimons 1996).

Lake Michigan: The Hamilton Reef near Muskegon was built in 1980 to attract and concentrate fish. Within 2 years the reef was colonized by at least 10 species of invertebrates, and 7 species of forage fish. The artificial reef was shown to be successful in concentrating cool water fish, especially yellow perch. Gill netting revealed significantly higher numbers of yellow perch over the reef than at reference sites. Data from fry traps indicated that several fish species were able to spawn successfully at the reef site, although there was no evidence for lake trout spawning (Kevern *et al.* 1985). Conversely, lake trout were attracted to spawn, and had high rates of egg deposition at new, unfouled substrate provided by submerged cobble reefs added to Port of Indiana breakwaters in southern Lake Michigan (Marsden & Chotkowski 2001). Campbell and Cook reefs are also incidental artificial reefs comprised of riprap scour protection fields associated with the intakes and discharges of two power plants in southeastern Lake Michigan. Intensive biological monitoring at these sites for nearly a decade revealed that significant numbers of yellow perch, alewife and slimy sculpin utilized and concentrated around these novel habitats. The investigators concluded that artificial reefs can be effective as fish attracting devices, though only seasonally and in limited areas (Rutecki *et al.* 1985).

Central basin of Lake Erie: In the late 1980's, two artificial reefs were built to improve catch rates for anglers. Underwater video and diver assessments conducted monthly during 1992 and 1993 revealed that total seasonal numbers of fish were significantly higher at the reef than at the control sites, indicating that these reefs were effective fish concentrating devices for targeted species including smallmouth bass and walleye (Kelch & Reutter 1995).

Western Lake Ontario: A small artificial reef built in the early 1980s , also to improve angling opportunity, was found to have slightly higher numbers of fish—including rock bass, yellow perch, white perch, brown trout and white sucker—in comparison to nearby bedrock sites, even only a few months after it was built (Gannon *et al.* 1985).

Furthermore, it is not known to what extent noise and other disturbances associated with the wind power project will affect the preference of Great Lakes fish species to utilize the newly created habitat.

8.3 Invasive species

In addition to attracting native species of ecological or angling importance, artificial reefs in the Great Lakes also provide ideal habitat for a number of undesirable, non-indigenous species. For example, lakebeds characterized by cobble, rock or rip rap substrates represent the preferred habitat of the round goby, an aggressive invasive benthic fish which nests in the cavities of rocks or boulders (Jude & DeBoe 1996). Furthermore, it is well known that non-native dreissenid mussels including the zebra and deeper water quagga mussel will attach and grow on essentially any hard substrate including rocks, boulders, pilings and most other submerged man-made structures (Jude & DeBoe 1996). The hard substrate provided by artificial reefs—whether they are installed as fisheries management tools or incidentally created by the installation of offshore structures—would provide new habitat for these species and potentially contribute to their range or population expansion.

For artificial reefs and other offshore structures (including wind turbine foundations) installed in the Great Lakes, it is expected that dreissenid mussels will not only be early colonizers but will also dominate the fouling communities that develop over time. Nearly all of the shallow reefs, natural or artificial, in the Great Lakes are now fouled to some extent by zebra mussels (Marsden & Chotkowski 2001). Zebra mussels tend to be limited to the warmer, shallower waters of the Great Lakes while the more recently introduced quagga mussels have extended their ranges to deeper and cooler waters. As a result, structures or artificial reefs installed at greater depths may escape fouling by the zebra mussel, but may still be colonized by its cooler-water counterpart.

Round gobies are currently limited to available rocky habitat in the Great Lakes. However, the creation of new rocky substrate either by artificial reefs or scour protecting revetments is expected to increase suitable habitat and thereby increase the carrying capacity for round gobies in the Great Lakes ecosystem (Raffenberg & Dettmers 2000). Monitoring studies have revealed that among the fish species associated with existing artificial reefs, round gobies are often among the most prevalent or abundant, especially at artificial reefs in Lake Michigan (Creque *et al.*

2006; Yauck 2009). In addition to providing nesting sites, artificial rocky reefs could also provide an ideal forage base for round gobies. Round gobies prey on dreissenid mussels, among other things, so the prevalence of this preferred food source upon artificial structures could further serve to attract and support large numbers of gobies at artificial reefs. Round gobies are typically associated with the nearshore zone (Box 1), corresponding to the depth and temperature tolerance ranges of zebra mussels, their preferred prey. However, if available habitat permits, the expansion of the more recently introduced quagga mussels into deeper water could favour the spread of round gobies away from nearshore areas and into deeper offshore waters (Jude & DeBoe 1996).

The presence of these invasive species at artificial reefs could counteract the potential benefits to native fish species proffered by the creation of new foraging, spawning or nursery habitat. Both round gobies and quagga mussels have been shown to directly or indirectly impact the fitness of native fish species. The invasion of dreissenid mussels in the Great Lakes has been linked to declines in the abundance of the amphipod *Diporeia* (Madenjian *et al.* 2010) and native unionid bivalves (Schloesser *et al.* 1996) – important prey items to many native fish species. The colonization of artificial reefs by zebra mussels has also been linked to reduced egg deposition and increased damage to eggs of lake trout (Marsden & Chotkowski 2001). Round gobies have been shown to dominate resources and outcompete native fish species (Bergstrom & Mensinger 2009) and predate upon the eggs of other fish including lake trout (Jonas *et al.* 2005).

Non-indigenous species represent a significant threat to native biodiversity in the Great Lakes. The creation of structures such as wind turbine foundations that act as artificial reefs may provide new habitat for these species and thereby potentially contribute to the expansion of their populations. Furthermore, depending on where the structures are installed, a network of incidental artificial reefs that represent ideal habitat for non-indigenous species could create corridors that link previously unconnected areas, thereby acting as stepping stones for colonization and further range expansion of these undesirable species. The potential creation of such corridors for expansion is therefore a serious concern related to the installation of incidental artificial reefs structures such as wind turbine foundations.

9. Effects on fishing and aquaculture activities

Within the Great Lakes, most recreational fishing activity occurs within several kilometres of shore (i.e. in the nearshore zone), or within safe running distances for small motor vessels. The potential for offshore wind power projects to impact recreational fisheries will therefore depend upon how far offshore they are installed, and whether or not their locations overlap with recreational angling sites. If wind energy facilities are located in areas accessible to anglers, they could have an impact on this economically important industry.

Given that the vertical structure and heterogeneous hard substrate created by the turbine masts, foundations and scour protecting materials have the propensity to serve as artificial reefs and attract aggregations of fish, the occurrence of wind power projects in certain areas of the offshore environment could enhance local recreational fisheries. As detailed above, nearshore artificial reefs that have been built in the Great Lakes have a demonstrated potential to attract valued sport fish including yellow perch, walleye and smallmouth bass. These reefs have been utilized by recreational anglers who acknowledge the value of being able to target their efforts at known locations, and who have also reported high catch rates of desired species at some of these artificial reef sites (Kelch & Reutter 1995). If wind power project areas are not excluded for recreational fishing activities —because of either their distance from shore or for navigational safety reasons—it is anticipated that anglers might target these locations if the turbine structures are known to concentrate desired species of fish. While this could benefit local anglers by way of higher catch rates and ease of locating fish aggregating areas, the resulting increase in fishing effort and harvest biomass could have deleterious effects on fish stocks if they are consequently over-exploited (Inger *et al.* 2009).

The Great Lakes also support a large and economically valuable commercial fishing industry, utilizing resources further from shore to a greater extent than the recreational angling sector, although often still within the nearshore zone. As a result, there is a greater potential for offshore wind facilities in the Great Lakes to overlap with and impact upon commercial fisheries than recreational fisheries, depending on project placement. It is less likely that larger-scale operations and fishing vessels will be able to access areas in the immediate vicinity of wind turbine structures. Collision risks associated with proximity to the turbine towers, and the

potential for entanglement of fishing gear among the foundations and scour protecting structures will probably require that many or all commercial fishing activities will have to avoid areas close to wind turbines. Where this occurs, conflicts over loss of access could arise. This also raises concern over the fact that there are more than 160 First Nations communities within the Great Lakes basin, many of which are involved in sustenance fishing or participate in Ontario's commercial fishery. Thus, spatial planning of offshore wind sites will require consideration of Aboriginal and Treaty Rights as they pertain to fisheries in the Great Lakes.

Commercial cage aquaculture in Ontario largely occurs in the North Channel of Lake Huron and Georgian Bay—in the Manitoulin-La Cloche region—and includes First Nations aquaculture sites. Rainbow trout are the species most commonly reared in these cage culture facilities, with roughly 3000 metric tonnes produced yearly. Impacts to aquaculture will likely only arise if offshore wind power projects are sited in close proximity to these facilities, and even so would largely be limited to the construction phase when effects from loud noises and sediment re-suspension are greatest. Noise during the operational phase of wind power projects could in fact be of little consequence to caged rainbow trout, as equipment and vessel noise within aquaculture facilities themselves generate sound levels that exceed ambient noise. A recent experiment indicated that rainbow trout hearing sensitivity, growth, survival, stress, and disease susceptibility were not negatively impacted by noise levels common to recirculating aquaculture systems (Wysocki *et al.* 2007). The probability that offshore wind facilities will impact aquaculture activities in the Great Lakes is therefore expected to be minimal.

Owing to the fact that the presence of offshore wind facilities could necessarily restrict access of certain gear types and fishing activities in the vicinity of turbine structures, wind power projects have the potential to act as *de facto* fisheries exclusion or partial no-take zones, regardless of whether they are enforced or not (Fayram & de Risi 2007; Inger *et al.* 2009). Marine protected areas (MPAs) or reserves have recently been promoted and used as a tool for fisheries management in attempts to conserve and restore ecologically important fish species and habitats (Roberts *et al.* 2001). By spatially limiting the pressure on certain stocks, and reducing damage to benthic ecosystems wrought by bottom trawling, for example, MPAs could promote an increase in local fish density and biomass, as well as increased fish diversity within the area. Thus, if designed effectively, these fisheries exclusion zones can theoretically act as a source of

larvae, juvenile and adult fish to surrounding areas, in this way enhancing nearby fisheries through what is known as a spill-over effect. The probability that offshore wind power projects in the Great Lakes could act as effective MPAs and increase local fish biomass remains unclear, but will certainly depend on where they are located, their design, and the degree of fisheries exclusion that results from their presence.

During the operational phase, the benefits or adverse effects of wind power projects on commercial or recreational fisheries will largely be manifested through their potential to act as artificial reefs and fish aggregating devices, or as MPAs. Operational noise and potential impacts from electromagnetic fields are not expected to have significant effects on local fisheries, for example. Conversely, disturbance from high levels of noise and turbidity during the construction and installation phase would have a greater impact on fisheries in the area. As discussed above, the loud noises from pile driving and other construction activities are likely to result in avoidance of the wind power project area by most mobile fish species, and could therefore alter the catch rates of commercial and recreational fisheries. On the California coast, for example, catch per unit effort of targeted rockfish species were more than halved after exposure to seismic air-gun blasts (Skalski *et al.* 1992), while in the Barents Sea, reductions in trawl and longline catches of commercially harvested cod and haddock were also noted up to 18 nautical miles away from the source of seismic air-gun blasts (Engas *et al.* 1996).

Another potential concern to both recreational and commercial fisheries in the Great Lakes is the possible release of any sediment-bound contaminants during dredging and cable laying. If persistent organic pollutants or heavy metals are disturbed and re-mobilized, they could be taken up by nearby biota and subsequently bioaccumulate up the food chain. Contaminants will be highest in larger fish species—such as those targeted by anglers for consumption—and could therefore pose a risk to human health.

10. Discussion

In this report we have identified what we expect to be the major categories of effects associated with the development of offshore wind facilities in the Great Lakes as they relate to fish and fish habitat. Clearly, some of the expected impacts of wind turbine installation and operation pose a

greater threat to local fish and fish habitat than others (Table 1); some effects will be temporary while others are more long-lasting, and some might only impact specific fish species or life history stages. Furthermore, the effects of offshore wind development could be cumulative, not only through time but also as more projects are installed throughout the lakes. As a result, consideration should be given to potential ecosystem level changes in addition to impacts at the scale of individual installations. Finally, while there could be several adverse impacts of offshore wind power projects to Great Lakes fish, benefits are also possible including the creation of artificial reefs and marine protected areas. More research is needed to evaluate how significant these benefits will be and how they might balance against related adverse effects.

10.1 Critical habitat and key species

The Great Lakes comprise a diversity of habitats, from wetlands to beaches to rocky shoals and more. Each of these habitats hosts its own unique assemblage of species and is utilized by various life history stages of fish at different times of the year. Some of this habitat might be essential to a species in order to survive and complete its life cycle; this habitat is deemed critical habitat. As we have outlined in this report, offshore wind power projects have the potential to affect fish habitat in a variety of ways, for example in the digging of trenches for laying submarine cables or in the destruction of benthic habitat beneath a turbine foundation. Depending on the rarity of the habitat or the species utilizing that habitat, an offshore wind power project placed within or near critical habitat could have a particularly negative environmental impact. It will therefore be imperative to quantify and characterize the habitat that is within a proposed wind power project area and along its cable route and to document its utilization by all life stages of fish at various times of the year. Appropriate adjustments, preventative action, and mitigation measures can then be carefully planned and carried forward as needed. The creation of protected areas, where offshore wind power projects are not permitted, should also be considered as a means of protecting critical habitat.

Although each fish species within the Great Lakes has its own role to play within the food web, some species are of particular importance for economic, social, or ecological reasons. One group of species given special consideration are those which are listed under the Species at Risk Act (SARA 2002). Most of the fish in the Great Lakes region that have been listed under the Species at Risk Act occupy riverine or shallow-waters generally located at depths less than 10 m. In

many cases, these habitats will be located far enough away from arrays of offshore turbines to be outside the range of impact. However, impacts to these species are possible if an offshore wind power project is located in particularly shallow water, if effects extend beyond a wind power project area, and where submarine cables make landfall. As in the case of critical habitat, appropriate pre-construction surveys need to be done in order to determine which species are present at different times of the year, so that appropriate action can be taken in the event that an important species of fish is present and likely to be adversely impacted.

10.2 Differences between offshore wind power projects and other offshore development

Offshore development projects are commonplace in the Great Lakes, including the construction of bridges and piers and coastal engineering works for shoreline protection or modification. While we may look to the effects of these activities on local fish and fish habitat in order to predict the response of aquatic communities to offshore wind power project developments, the unique character of wind turbine location, construction and operation means that few comparisons may effectively be drawn with existing projects. Not only will disturbance from noise and other aspects of turbine construction be of longer duration throughout the installation phase of large offshore wind facilities—which could take on the order of months to a year or more—but there will also be noise and other effects associated with their operation, which is not the case for most other installation types. Also, where most construction activity in the Great Lakes currently occurs close to shore, wind turbines will often be situated further offshore and therefore have effects on a different suite of species and habitat types. Thus, an understanding of the effects of other development or construction projects in the Great Lakes on local biotic and abiotic conditions, while perhaps useful in a general sense, is insufficient to be able to accurately assess how the construction and operation of offshore wind projects might affect fish species and habitat.

10.3 Options to reduce negative impacts and promote benefits

Drawing from the experiences of existing wind turbine and other offshore development projects, several strategies for mitigating some of the potentially harmful impacts of offshore wind power projects to Great Lakes fish and fish habitat can be identified. As a case in point, methods of reducing the high impact noise levels associated with pile driving have been developed and

employed for the construction of other offshore structures including oil and gas rigs and bridge and pier installations. Adopting a slow or soft-start, whereby the initial hammer strikes are made with less force and at a reduced frequency than the eventual full-force, full-speed pile driving has been recommended in order to warn nearby mobile species and scare them away before damaging noise levels are reached. Other options to reduce underwater noise levels include the use of vibropiling instead of impact pile driving, or using wood, nylon or micarta pile caps to reduce the sound generated by the pile (Caltrans 2009; Popper & Hastings 2009). In addition, the use of cofferdams or air bubble curtains has also proven successful in some cases in reducing noise transmission from the pile driving source and thereby limiting the area of injury for aquatic organisms (Caltrans 2009).

Options to reduce the detection distance of and mitigate the potential behavioural interference from electromagnetic fields include improving cable armour or sheathing or burying the cables as deep as possible within the sediment (Gill *et al.* 2009; Petersen & Malm 2006). It has also been shown that a technique of core twisting can substantially reduce the magnetic field in proximity to the cable (Ohman *et al.* 2007). Additionally, the transmission cable route could be modified or adjusted so as to avoid intersecting any known migratory routes of EMF-sensitive species. In order to reduce the potential for re-suspension of sediments, high levels of turbidity and possible release of contaminants upon dredging for cable burial or during foundation installation, containment measures such as the use of silt curtains are recommended (Knott *et al.* 2009). However, silt curtains might not be as effective within a Great Lakes setting where water can often be rough and waves too high. Perhaps more importantly, however, pre-construction sediment surveys throughout the proposed project area should be conducted as part of the site selection process in order to avoid dredging in highly contaminated areas.

The potential for offshore wind turbine structures to act as artificial reefs and create new spawning or foraging areas for native species of Great Lakes fish will depend largely upon location and depth, design and spatial arrangement, and certainly upon the identity of fish species likely to use the new habitat. If the aim is to attract specific species of fish, an understanding of their natural habitat requirements or preferences would obviously be essential in order that appropriate materials are used in creating these structures. Methods of modifying aquatic habitats for the benefit of various species have been developed, and the existing body of scientific

literature on artificial reef design is quite extensive. This information should be reviewed in more detail if turbine structures are intended to serve as functional artificial reefs.

While the layout of offshore wind turbine arrays is typically designed to maximize wind energy capture, spacing to enhance habitat use from a biological perspective could also be considered (Linley *et al.* 2007). There is evidence, for example, that the installation of artificial reefs in a fractal pattern maximizes habitat complexity and biological productivity (Lan *et al.* 2004). Finally, in order to reduce the potential for wind turbine structures to act as stepping stones for the range expansion of invasive species, care must be taken not to install them in corridors between colonized and non-colonized areas of the Great Lakes.

10.4 Detecting the impacts of offshore wind power projects

Clearly, there are a number of approaches that may be taken in order to reduce or mitigate some of the negative impacts, as well as to enhance or promote the potential benefits of offshore wind developments to Great Lakes fish and fish habitat. However, in order for any of these measures to be successful, it is necessary to first have a clear understanding of the identity and ecology of the fish community that inhabits the area of a proposed wind energy project, including knowledge of the seasonal movement patterns of different species into and out of the area throughout the year. For example, many of the harmful impacts that arise during project construction could potentially be reduced if shoals used for spawning or egg laying are avoided, or if activities such as dredging, drilling and pile driving are timed so that they do not interfere with the spawning or hatching seasons of nearby sensitive species.

Monitoring of fish abundance and diversity, as well as a thorough characterization of existing habitat types within the project area before construction begins is necessary in order to establish a baseline for comparison with later phases of development. Similarly, ongoing monitoring programmes that adhere to existing scientific protocols and standards for fish stock assessments and benthic habitat evaluation are also critical in order to gauge the relative impact of various aspects of wind power project installation and operation on local fish populations and habitat resources. By providing a means to detect and measure these impacts, pre- and post-construction monitoring will also help to guide future environmental impact assessments. Moving forward, this will allow an adaptive management approach to be taken as offshore wind developments in

the Great Lakes expand. A more thorough discussion of mitigation measures and methods for detecting impacts will be included in the second, accompanying report.

10.5 Concluding remarks

The proposed development of offshore wind power projects within the Great Lakes has the potential to generate a significant amount of renewable energy for the province of Ontario as well as for bordering American states. While the installation of wind turbines in the offshore environment will certainly have some impacts upon the aquatic ecosystem and its inhabitants, including economically and ecologically valuable species of fish as detailed above, these need to be weighed with the benefits of a renewable, low carbon-emission source of energy. Fossil-fuel based energy production is recognized as the prime culprit contributing to the global climate change phenomenon—a stressor with potentially significant negative consequences to Great Lakes fish and fish habitat that, as a whole, could very well surpass any adverse impacts from offshore wind development. Although the effects of offshore wind power projects detailed above might not be inconsequential, the spatial scale over which most individual effects are felt could be relatively small in relation to the size of the Great Lakes. The physical area assumed by individual turbine foundations and scour-protecting revetments, for example, would only be a small fraction of the total project area. Scaling up to the level of the entire Great Lakes ecosystem, this fraction gets even smaller. Thus, if care is taken to properly site project locations, avoid sensitive habitat areas, employ available options or continue to develop new options for mitigation, and conduct appropriate biological monitoring, the potential impacts of offshore wind power production could in fact be minimal.

Appendices

Appendix A. Summary chart of various field and laboratory experiments designed to test the impacts of different noise levels on the physiology and behaviour of marine and freshwater fish. Species in bold denote fish that inhabit the Great Lakes.

Species	Effect type	Description of effect	Noise level and duration	Description of study	Reference
Goldfish, tilapia	Physiological	Temporary shift in goldfish hearing threshold after 24hr; no hearing loss in tilapia after 28 days	0.1-10 kHz, 170 dB re 1 uPa of white noise for 7-28 days	Laboratory experiment	(Smith *et al.* 2004a)
Northern pike, **lake chub**, and broad whitefish	Physiological	Temporary hearing loss in pike and chub; no threshold shift in broad whitefish	Air gun shots, mean peak sound pressure levels 205-210 re 1 µPa	Fish held in shallow-water cages and exposed to airgun shots at distance of 15 m	(Popper *et al.* 2005; Song *et al.* 2008)
Oscar fish	Physiological	Sensory cell damage to inner ear noted only after 4 days post-exposure	300 Hz and 180dB for 1 hour	Laboratory experiment	(Hastings *et al.* 1996)
Atlantic cod	Physiological	Damage to sensory cells (loss of ciliary bundles) in inner ear	50-400 Hz at 180 dB for several hours	Laboratory experiment	(Enger 1981)
Pink snapper	Physiological	Extensive damage to sensory hair cells in inner ear; damage increased with post-exposure period	Max = 180 dB re $1\mu Pa^2sec^{-1}$	Fish held in underwater cages and exposed to repeated signals from an air-gun	(McCauley *et al.* 2003)
Blue gouramis, goldfish	Physiological	Blue gouramis: acoustic stunning and loss of consciousness after 10 min, mortality after 30 min; Goldfish: damage to auditory hair cells and mortality after 1 hr	Blue gouramis: 400 Hz tone at 198 dB re 1 uPa; goldfish: 250 Hz tone at 204 dB re 1 uPa	Laboratory experiments	(Hastings 1995)
Chinook salmon smolts	Physiological	Small but significant threshold shift (loss of hearing), recovery after 7 days	Barge holding tank noise, <400Hz, up to 136 dB re 1 uPa for 33.5-58.5 hr	Fish transported in barge with elevated noise levels in holding tanks	(Halvorsen *et al.* 2009)

Species	Effect type	Description of effect	Noise level and duration	Description of study	Reference
Fathead minnow	Physiological	Threshold shift in hearing; longer recovery time (> 14 days) with longer exposure	0.3-2.0 kHz, 142 dB re 1 uPa, 1-24 hr exposure	Laboratory experiment	(Scholik & Yan 2002)
Rainbow trout	Physiological	20 dB auditory threshold shift; recovery within 24-48 hr; no inner ear tissue damage observed	High intensity, low frequency sonar; 160-325 Hz, 193 dB re 1 uPa	Laboratory experiment	(Popper *et al.* 2007)
Juvenile pinfish and spot croaker	Physiological	Histopathological examination revealed hyperemia in swim bladder, coagulative liver necrosis, rupture of pancreas	Exposure to pressure waves from underwater explosions; peak pressure of 236 dB re 1 uPa	Fish held in plastic bags on either side of a boat at various distances from explosion source	(Govoni *et al.* 2003)
Common carp, European perch, gudgeon	Physiological	Endocrine stress response, increase in cortisol secretion in all 3 species	Boat noise, 153 dB re 1 uPa for 30 min	Laboratory experiment	(Wysocki *et al.* 2006)
Goldfish	Physiological	Significantly higher levels of blood plasma cortisol within 10 min. of noise exposure	White noise, 0.1-10 kHz, 160-170 dB re 1 uPa,1-21 days	Laboratory experiment	(Smith *et al.* 2004b)
Rockfish sp.	Behavioural	Startle and general alarm response, change in schooling formations and behaviour	Exposure to air gun sounds, 160-205 dB re 1 uPa	Fish held in field enclosures	(Pearson *et al.* 1992)
Haddock and cod	Behavioural	Significant reductions in trawl catches after seismic surveys up to 18 nautical miles away	Exposure to air gun shootings; 10-150 Hz, max. peak pressure of 249 dB 1 m from source	Trawl catch study conducted in the field	(Engas *et al.* 1996)
Rockfish sp.	Behavioural	52% decrease in catches in area exposed to air gun emission	Single air gun emission at 186-191 dB re 1 uPa	Catch per unit effort measured in the field	(Skalski *et al.* 1992)

Species	Effect type	Description of effect	Noise level and duration	Description of study	Reference
Red-mouthed goby and Mediterranean damselfish	Behavioural	Goby spent significantly more time inside shelters; damselfish spent significantly less time caring for nests	Exposure to recorded sound from tourist ferry boat (142 dB re 1 uPa) and 5m fibreglass boat (162 dB re 1 uPa) for 5 min.	*In situ* experiments on individual fish in artificial reef of a marine reserve; underwater cameras monitored behaviour	(Picciulin *et al.* 2010)
Bluefin tuna	Behavioural	Changes in speed and direction of swimming; altered schooling structure and behaviour	70-20000 Hz, 100-135 dB re 1 uPa	Tuna held in large nets with boats passing by, observed using scuba divers and underwater cameras	(Sara *et al.* 2007)

Appendix B. Sound pressure levels associated with different wind power project activities.

Activity	Phase	Frequency range	Source sound pressure levels (re 1 µPa @ 1m)	References
Geophysical surveys—boomers and sparkers	Pre-construction	Not reported	215-230 dB	(Nedwell & Howell 2004)
Geophysical surveys—air guns	Pre-construction	Not reported	Individual: 216-232 dB Array: 235-259 dB	(Nedwell & Howell 2004)
Boat engine noise	Pre-construction/ Construction/ Operational	Tonal, narrowband sound and broadband sound at specific frequencies	135-190 dB	(Codarin *et al.* 2009; Nedwell & Howell 2004; Picciulin *et al.* 2010; Scholik & Yan 2002; Wysocki *et al.* 2006)
Construction noise (combined noise from boats, dredging, drilling, pile driving etc.)	Construction	Broadband	Up to 260 dB	(Nedwell *et al.* 2003a)
Dredging	Construction	Low frequency noise within range of 20-1000 Hz; peak frequency 80-200 Hz	Up to 178 dB	(Madsen *et al.* 2006; Nedwell & Howell 2004)
Diver use of power tools for cutting/drilling/welding	Construction	Broadband	Up to 200 dB	(Nedwell & Howell 2004)
Drilling	Construction	Not reported	145-192 dB	(Nedwell & Howell 2004)
Cable trenching	Construction	Not reported	Up to 178 dB	(Nedwell *et al.* 2003a)
Pile-driving (single-strike sound levels of different pile sizes/types)	Construction	Highly broadband (frequencies up to 10 kHz); Peak energy focussed between 100 Hz- 2kHz; Sound max. <500 Hz	177-260 dB	(Bailey *et al.* 2010; Caltrans 2009; Madsen *et al.* 2006; Mueller-Blenkle *et al.* 2010; Nedwell *et al.* 2003a)
Operating noise (e.g. aerodynamic noise from rotor blades, noise from gear box, structural vibrations)	Operational	Low frequency, between 1-1000 Hz; Peak sound levels between 15-30 Hz and 100-200 Hz	80-153 dB	(Gill 2005; Nedwell & Howell 2004)
Underwater blasts/ detonations	Decommissioning	Not reported	Up to 272 dB	(Nedwell & Howell 2004)

Appendix C. Summary of various field and laboratory experiments designed to test the impacts of pile driving noise on the physiology and behaviour of fish. Species in bold denote fish that inhabit the Great Lakes.

Species	Description of effect	Type of study	Sound pressure level/distance from source	Reference
Shiner surfperch, **steelhead trout**	More trauma in fish exposed to pile driving noise than unexposed fish; no difference in mortality	Field experiment; fish held in cages at various distances from piles	158-182 dB (re 1$\mu Pa^2 s^{-1}$); 23-314 m from the pile	(Caltrans 2004)
Sacramento blackfish	More damage to fish closer to the source than further away; no damage to fish exposed to < 183 dB	Field experiment; fish held in cages at various distances from piles	<183 -193 dB (re 1 µPa); 45 -850 m from pile	(Abbott & Bing-Sawyer 2002)
Juvenile coho salmon	Subtle behavioural changes noted, but no difference in mortality or histopathology between individuals held close to or far away from small steel piles	Field experiment; fish held in cages at various distances from piles	Sound exposure levels of 179 dB (re 1 $\mu Pa^2 sec^{-1}$) within several meters of the piles	(Ruggerone *et al.* 2008)
Sole, cod	Changes in the swimming speed and direction of sole; changes in swimming speed and initial freezing responses of cod	Laboratory experiment; pile-driving noise played back	Reactions in sole occurred between 144-156 dB (re 1 µPa); reactions in cod noted between 140-161dB (re 1 µPa)	(Mueller-Blenkle *et al.* 2010)
Brown trout	No reaction response to pile driving noise	Field experiment; fish held in cages at various distances from piles	134 dB (re 1 µPa); 400 m from pile	(Nedwell *et al.* 2003b)

Appendix D. Scientific and common names of fish species listed throughout the report.

Alewife	*Alosa pseudoharengus*
American eel	*Anguilla rostrata*
Atlantic cod	*Gadus morhua*
Bluefin tuna	*Thunnus thynnus*
Blue gouramis	*Trichogaster trichopterus*
Broad whitefish	*Coregonus nasus*
Brook trout	*Salvelinus fontinalis*
Brown bullhead	*Ameiurus nebulosus*
Brown trout	*Salmo trutta*
Burbot	*Lota lota*
Channel catfish	*Ictalurus punctatus*
Channel darter	*Percina copelandi*
Chinook salmon	*Oncorhynchus tshawytscha*
Chum salmon	*Oncorhynchus keta*
Coho salmon	*Oncorhynchus kisutch*
Common carp	*Cyprinus carpio*
Eastern sand darter	*Ammocrypta pellucida*
Emerald shiner	*Notropis atherinoides*
European eel	*Anguilla anguilla*
European perch	*Perca fluviatilis*
Fathead minnow	*Pimephales promelas*
Goldfish	*Carassius auratus*
Gudgeon	*Gobio gobio*
Haddock	*Melanogrammus aeglefinus*
Lake chub	*Couesius plumbeus*
Lake sturgeon	*Acipenser fulvescens*
Lake trout	*Salvelinus namaycush*
Lake whitefish	*Coregonus clupeaformis*
Largemouth bass	*Micropterus salmoides*
Medaka	*Oryzias latipes*
Mediterranean damselfish	*Chromis chromis*
Mottled sculpin	*Cottus bairdii*
Muskellunge	*Esox masquinongy*
Northern pike	*Esox lucius*
Oscar	*Astronotus ocellatus*
Pinfish	*Lagodon rhomboides*
Pink snapper	*Pagrus auratus*
Rainbow/steelhead trout	*Oncorhynchus mykiss*
Red-mouthed goby	*Gobius cruentatus*
Roach	*Rutilus rutilus*
Rock bass	*Ambloplites rupestris*
Rockfish	*Sebastes* spp.
Round goby	*Neogobius melanostomus*
Sacramento blackfish	*Orthodon microlepidotus*
Sea lamprey	*Petromyzon marinus*
Shiner surfperch	*Cymatogaster aggregate*
Shortjaw cisco	*Coregonus zenithicus*
Silver chub	*Macrhybopsis storeriana*
Slimy sculpin	*Cottus cognatus*
Smallmouth bass	*Micropterus dolomieu*
Sockeye salmon	*Oncorhynchus nerka*
Sole	*Solea solea*
Spot croaker	*Leiostomus xanthurus*
Three-spined stickleback	*Gasterosteus aculeatus*
Tilapia	*Oreochromis niloticus*
Walleye	*Sander vitreus*
White crappie	*Pomoxis annularis*
White perch	*Morone americana*
White sucker	*Catostomus commersonii*
Yellow perch	*Perca flavescens*

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